

Archaeological Remote Sensing:
Visualisation and analysis of grass-dominated environments
using airborne laser scanning and digital spectra data

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Abstract

The use of airborne remote sensing data for archaeological prospection is not a novel concept, but it is one that has been brought to the forefront of current work in the discipline of landscape archaeology by the increasing availability and application of airborne laser scanning data (ALS). It is considered that ALS, coupled with imaging of the non-visible wavelengths using digital spectral sensors has the potential to revolutionise the field of archaeological remote sensing, overcoming some of the issues identified with the most common current technique of oblique aerial photography. However, as with many methods borrowed from geographic or environmental sciences, archaeologists have yet to understand or utilise the full potential of these sensors for deriving archaeological feature information.

This thesis presents the work undertaken between 2008-11 at Bournemouth University that aimed to assess the full information content of airborne laser scanned and digital spectral data systematically with respect to identifying archaeological remains in non-alluvial environments. A range of techniques were evaluated for two study areas on Salisbury Plain, Wiltshire (Everleigh and Upavon) to establish how the information from these sensors can best be extracted and utilised. For the Everleigh Study Area archive airborne data were analysed with respect to the existing transcription from archive aerial photographs recorded by English Heritage's National Mapping Programme. At Upavon, spectral and airborne laser scanned data were collected by the NERC Airborne Research and Survey Facility to the specifications of the project in conjunction with a series of ground-based measures designed to shed light on the contemporary environmental factors influencing feature detectability.

Through the study of visual and semi-automatic methods for detection of archaeological features, this research has provided a quantitative and comparative assessment of airborne remote sensing data for archaeological prospection, the first time that this has been achieved in the UK. In addition the study has provided a proof of concept for the use of the remote sensing techniques trialled in temperate grassland environments, a novel application in a field previously dominated by examples from alluvial and Mediterranean landscapes. In comparison to the baseline record of the Wiltshire HER, ALS was shown to be the most effective technique, detecting 76% of all previously known features and 72% of all the total number of features recorded in the study. Combining the spectral data from both January and May raised this total to 83% recovery of all previously known features, illustrating the value of multi-sensor survey.

It has also been possible to clarify the strengths and weaknesses of a wide range of visualisation techniques through detailed comparative analysis and to show that some techniques in particular local relief modelling (ALS) and single band mapping (digital spectral data) are more suited to

the aims of archaeological prospection than others, including common techniques such as shaded relief modelling (ALS) and True Colour Composites (digital spectral data). In total the use of “non-standard” or previously underused visualisation techniques was shown to improve feature detection by up to 18% for a single sensor type.

Investigation of multiple archive spectral acquisitions highlighted seasonal differences in detectability of features that had not been previously observed in these data, with the January spectral data allowing the detection of 7% more features than the May acquisition. A clearer picture of spectral sensitivity of archaeological features was also gained for this environment with the best performing spectral band lying in the NIR for both datasets (706-717nm) and allowing detection c.68% of all the features visible across all the wavelengths. Finally, significant progress has been made in the testing of methods for combining data from different airborne sensors and analysing airborne data with respect to ground observations, showing that Brovey sharpening can be used to combine ALS and spectral data with up to 87% recovery of the features predicted by transcription from the contributing source data.

This thesis concludes that the airborne remote sensing techniques studied have quantifiable benefit for detection of archaeological features at a landscape scale especially when used in conjunction with one another. The caveat to this is that appropriate use of the sensors from deployment, to processing, analysis and interpretation of features must be underpinned by a detailed understanding of how and why archaeological features might be represented in the data collected. This research goes some way towards achieving this, especially for grass-dominated environments but it is only with repeated, comparative analyses of these airborne data in conjunction with environmental observations that archaeologists will be able to advance knowledge in this field and thus put airborne remote sensing data to most effective use.



Tag cloud of the 100 most common words in this thesis. Size reflects frequency of use.

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List of Publications

The following are a list of publications arising directly from the work presented in this thesis:

Journal Papers

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- Bennett, R., Welham, K., Hill, R.A., and Ford, A. 2012. A comparison of visualisation techniques for models created from airborne laser scanned data. *Archaeological Prospection*. *Archaeological Prospection* 19 (1)
- Bennett, R., Welham, K., Hill, R.A., and Ford, A. 2009. Beyond the picturesque: analysing the information content of airborne remotely sensed data for understanding prehistoric sites. *Archaeosciences revue d'archaémétrie: Mémoire de sol espace des hommes* 33: 259-262.

Book Chapters

- Bennett, R., Welham, K., Hill, R.A., and Ford, A. 2012. Using lidar as part of a multi-sensor approach to archaeological survey and interpretation. In D. C. Cowley and R. Opitz (eds) *Interpreting archaeological topography – airborne laser scanning, aerial photographs and ground observation*, Oxford: Oxbow Books
- Bennett, R., Welham, K., Hill, R.A., and Ford, A. 2011. Making the most of airborne remote sensing techniques for archaeological survey and interpretation. In D. C. Cowley (ed) *Remote Sensing for Archaeological Heritage Management*. EAC Occasional Paper, 99-107. Hungary: Archaeolingua

Conference Papers

- Bennett, R., Welham, K., Hill, R.A., and Ford, A. 2011. Pushing the Sensors: developing techniques for linking aerial and terrestrial remote sensing. Aerial Archaeology Research Group Conference (AARG) and European Association of Remote Sensing Laboratories (EARSel) Poznan, Poland
- Bennett, R., Welham, K., Hill, R.A., and Ford, A. 2011b. Pushing the Sensors: developing techniques for linking aerial and terrestrial remote sensing. Remote Sensing and Photogrammetry Society (RSPSoc) 2011, Bournemouth, UK
- Bennett, R., Welham, K., Hill, R.A., and Ford, A. 2011a. It's not all about history: how bespoke multi-sensor data acquisition can aid archaeological interpretation in non-arable landscapes. NERC ARSF Bi-Annual Workshop, Bournemouth, UK
- Bennett, R., Welham, K., Hill, R.A., and Ford, A. 2010b. Multisensor Airborne Remote Sensing Techniques for Archaeological Survey and Interpretation. AARG 2010, Bucharest, Romania
- Bennett, R., Welham, K., Hill, R.A., and Ford, A. 2010a. Analysing the Vegetation Information Content of Airborne Remotely Sensed Data with Respect to Improving Understanding of Archaeological Features. RSPSoc 2010, Cork, Ireland

- Bennett, R., Welham, K., Hill, R.A., and Ford, A. 2009. Analysing the information content of airborne remotely sensed data for archaeological prospection. AARG 2009, Siena, Italy
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List of Abbreviations and Common Terms

ALS	Airborne Laser Scanning
ALSF	Aggregates Levy Sustainability Fund
AP	Aerial Photograph / Aerial Photography
APFL	Average Percentage Feature Length, used in the Salisbury Plain Study to quantify percentage feature detectability
ARS	Airborne Remote Sensing. A term to describe any form of indirect measurement taken without physical contact with the feature under surveillance (NASA). Specifically used to denote sensors mounted on airborne platforms, e.g. ATM, CASI, ALS
ARSF	Airborne Research and Survey Facility (NERC)
ATM	Airborne Thematic Mapper – a digital spectral sensor
BDRF	Bidirectional Reflectance Distribution Function. A function that defines how light is reflected from an opaque surface
CASI	Compact Airborne Spectrographic Imager – a digital spectral sensor
CIR	Colour Infrared (of photographic film)
Defence Estates	Land management arm of the MoD
DEM	Digital Elevation Model
DTM	Digital Terrain Model
EA	Environment Agency
Eagle	Brand name for a type of VNIR hyperspectral sensor
EH	English Heritage
FCC	False Colour Composite
FSF	Field Spectroscopy Facility (NERC)
FWHM	Full Width at Half Maximum
GCP	Ground Control Points
GPR	Ground Penetrating Radar
GSA	Ground Surface Area
Hawk	Brand name for a type of SWIR hyperspectral sensor
HER	Historic Environment record (also known as a Sites and Monuments Record)
IDW	Inverse Distance Weighted – a method of interpolation from point to raster
IMU	Inertial Measurement Unit
kGPS	Kinematic Global Positioning System
Lidar	Light Detection and Ranging
LRM	Local Relief Model
LSM	Least Squares Matching - a method for determining the best value of an unknown quantity relating one or more sets of observations or measurements, especially to find a curve that best fits a set of data.
MIR	Middle Infrared - portion of the electromagnetic spectrum from 3000-5000nm
MoD	Ministry of Defence

NDVI	Normalised Difference Vegetation Index
NEODC	NERC Earth Observation Data Centre
NERC	Natural Environment Research Council
NIR / VNIR	Near Infra Red / Very Near Infra Red
NMP	National Mapping Programme (English Heritage)
PCA	Principle Components Analysis
PRN	Primary Record Number – the unique identifier in the HER
PTM	Polynomial Texture Mapping
RCAHMS	Royal Commission for Ancient and Historical Monuments Scotland
RCAHMW	Royal Commission for Ancient and Historical Monuments Wales
RCHME	Royal Commission for Historic Monuments England
Red Edge	The region of rapid change in reflectance of chlorophyll in the near infrared (680nm- 780nm).
Remote Sensing	Term to describe any form of indirect measurement taken without physical contact with the feature under surveillance (NASA). Includes geophysical techniques and satellite sensors in addition to airborne sensors
RGB	Red, Green, Blue or true colour imagery
RMSE	Root Mean Square Error - measure of the differences between predicted and observed values
SAC	Special Area of Conservation
sPCA	Selective Principal Components Analysis – where the inputs for PCA are selected from the available data based on prior analysis of suitability
SPTA	Salisbury Plain Training Area
SSSI	Site of Special Scientific Interest
SWIR	Short Wave Infra Red
TCC	True Colour Composite
UID	Unique identifier as ascribed to archaeological features in the Salisbury Plain Study

Table of Contents

Abstract	III
Acknowledgements	VI
List of Publications	VIII
List of Abbreviations and Common Terms	X
1 Introduction	1
2 Literature Review	6
2.1 Introduction	6
Remote Sensing for Archaeology	6
2.2 Archaeological Remote Sensing Techniques in Context	6
2.2.1 <i>Detecting Direct Effects</i>	7
2.2.2 <i>Detecting Proxy Effects</i>	8
2.3 Digital Spectral Imaging in Archaeological Research	10
2.3.1 <i>Introduction - Exploring the Invisible</i>	10
2.3.2 <i>Archaeological Applications of Digital Spectral Sensors</i>	12
2.4 Airborne Laser Scanning in Archaeological Research	17
2.4.1 <i>Introduction</i>	17
2.4.2 <i>ALS Research in Archaeology – The Aggregates Levy Sustainability Fund</i>	17
2.4.3 <i>Non-ALSF funded ALS Research</i>	20
2.5 Multi-Sensor Survey	22
2.5.1 <i>Complementarity</i>	22
2.5.2 <i>Barriers to Multi-Sensor Survey</i>	22
2.5.3 <i>Digital Data Fusion</i>	24
2.6 Summary of Archaeological Applications	25
2.7 Conclusions	26
Technical Literature Review	28
2.8 Introduction	28
2.9 Archaeological Feature Detection in Aerial Imagery	28
2.10 Digital Spectral Imaging	29
2.10.1 <i>General Theory</i>	29
2.10.2 <i>Plant Reflectance</i>	30
2.10.3 <i>Vegetation Analysis</i>	32
2.10.4 <i>Soil Analysis</i>	36
2.10.5 <i>Visualisation Techniques</i>	38
2.11 Airborne Laser Scanning (ALS)	39
2.11.1 <i>General Theory</i>	39
2.11.2 <i>Filtering</i>	42
2.11.3 <i>Interpolation</i>	42
2.11.4 <i>Intensity</i>	43
2.11.5 <i>Visualisation Techniques</i>	44
2.12 Geophysical Survey	48
2.12.1 <i>Earth Resistance Survey</i>	48
2.12.2 <i>Ground Penetrating Radar</i>	50
2.12.3 <i>Magnetometry (Fluxgate Gradiometry)</i>	50
2.13 Proposed Method Areas	51
2.14 Summary	52
3 Aim and Objectives	53
3.1 Aim	53

3.2 Objectives	53
4 Case Study Selection	55
4.1 Introduction	55
4.2 Case Study Rationale	55
4.3 Salisbury Plain	56
4.3.1 Location, Geology and Land Cover	58
4.4 Archaeological Interest	58
4.4.1 Previous Archaeological Investigations	59
4.4.2 Everleigh Study Area Environs	59
4.4.3 Upavon Study Area Environs	63
5 Data	67
5.1 Archaeological Data	67
5.1.1 Existing Archaeological Record (Everleigh and Upavon)	67
5.1.2 Preprocessing of the Wiltshire HER Data	68
5.2 Archive ARS Data (Everleigh)	70
5.2.1 Environment Agency Multispectral Data	71
5.2.2 Environment Agency ALS Data	73
5.2.3 Historic Aerial Photography	73
5.2.4 MoD Aerial Photography	73
5.2.5 NERC Earth Observation Data Centre (NEODC) Archive	74
5.2.6 Data Coverage and Sample Areas	74
5.3 Planned ARS Data Acquisition (Upavon)	77
5.3.1 Airborne Data Collection	78
5.3.2 Spectral Data Specifications and Preprocessing	78
5.3.3 ALS Specifications and Preprocessing	79
5.4 Ground Based Data Collection	81
5.4.1 Upavon Field Site Site 1, Coombe Down Enclosures	81
5.4.2 Upavon Field Survey Site 2 - Lidbury Camp	84
5.5 Summary	86
6 Method	87
6.1 Introduction	87
6.2 Project Organisation	89
6.2.1 Workflow	89
6.2.2 Selecting Software	89
6.3 Archaeological Feature Identification Protocol	91
6.3.1 Archaeological Feature Identification Protocol (Everleigh)	91
6.3.2 Archaeological Feature Identification Protocol (Upavon)	93
Digital Spectral Data Processing	95
6.4 Introduction	95
6.5 Land Use Mapping	95
6.6 4- Band Vertical Aerial Photographs	96
6.7 Archive Digital Spectral Data (Everleigh)	96
6.7.1 Single Band Mapping	96
6.7.2 True and False Colour Composites	97
6.7.3 Vegetation Indices	98
6.7.4 Principal Components Analysis (PCA)	99
6.8 Spectral Data Processing (Upavon)	101
6.8.1 Archaeological Feature Separability	101
Airborne Laser Scanning	103

6.9 Archive Airborne Laser Scanning Data (Everleigh)	103
6.9.1 <i>Shaded Relief Modelling</i>	104
6.9.2 <i>PCA of Shaded Relief Images</i>	105
6.9.3 <i>Slope, Aspect and Curvature</i>	105
6.9.4 <i>Horizon or Sky View Mapping</i>	105
6.9.5 <i>Local Relief Modelling</i>	106
6.9.6 <i>Polynomial Texture Mapping (PTM)</i>	107
6.9.7 <i>Feature Mapping</i>	107
6.10 Planned Airborne Laser Scanned Data (Upavon)	109
6.10.1 <i>Assessing the Accuracy of the Archaeological Feature Buffering</i>	109
6.10.2 <i>Assessing the Accuracy of the LRM Model</i>	109
6.10.3 <i>ALS Intensity Data Processing</i>	110
Combining Data from Multiple Airborne Sensors	111
6.11 Digital Data Combination	111
6.11.1 <i>Basic Raster Mathematics</i>	111
6.11.2 <i>Transformation Techniques</i>	111
Ancillary Data Processing	112
6.12 Archive Weather Information	112
6.12.1 <i>Average Rainfall</i>	112
6.12.2 <i>Soil Moisture Deficit</i>	113
6.13 Geophysical Data (Upavon)	114
6.13.1 <i>Fluxgate Gradiometry Survey</i>	114
6.13.2 <i>Earth Resistance Survey</i>	114
6.13.3 <i>GPR Survey</i>	115
6.14 Soil Sampling	117
6.14.1 <i>Soil Sample Collection</i>	117
6.14.2 <i>Soil Sample Processing</i>	118
6.15 Spectroradiometer Sampling	118
6.16 Kinematic Global Positioning System (kGPS) Survey	119
6.17 Comparing Ground Based and Airborne Data	121
6.17.1 <i>Correlation Analysis</i>	121
Comparing Across the Archive Airborne Data Sources	123
6.18 Statistical Analysis	123
6.18.1 <i>Binary Visibility</i>	123
6.18.2 <i>Comparing Land Use and Visibility</i>	123
6.18.3 <i>Comparing Feature Type and Visibility</i>	124
6.18.4 <i>Comparing Percentage Visibility</i>	124
6.19 Summary	125
7 Results - Individual Datasets	126
7.1 Introduction	126
Digital Spectral Data	127
7.2 Land Use Mapping	128
7.3 4-Band Aerial Photography (Everleigh)	129
7.4 Archive Spectral Data (Everleigh)	130
7.4.1 <i>Introduction</i>	130
7.4.2 <i>Single Band Mapping</i>	130
7.4.3 <i>Comparing Land Use and Visibility in the Single Band Data</i>	134
7.4.4 <i>Digital Combination of Spectral Bands</i>	136
7.4.5 <i>True and False Colour Composites</i>	136

7.4.6 <i>Principal Components Analysis (PCA)</i>	138
7.4.7 <i>Comparing Vegetation Indices</i>	143
7.5 <i>Spectral Data Processing (Upavon)</i>	148
7.5.1 <i>Introduction</i>	148
7.5.2 <i>Separation Index (SI)</i>	148
7.5.3 <i>Separation for Vegetation Indices</i>	152
ALS Data Processing	154
7.6 <i>Archive ALS Data Results (Everleigh)</i>	154
7.6.1 <i>Quality Assessment</i>	154
7.6.2 <i>Archive ALS Intensity Data</i>	154
7.6.3 <i>Shaded Relief Images</i>	155
7.6.4 <i>PCA of Shaded Relief Images</i>	156
7.6.5 <i>Slope, Aspect and Curvature</i>	161
7.6.6 <i>Horizon View</i>	162
7.6.7 <i>Local Relief Modelling</i>	165
7.6.8 <i>Comparing the ALS Visualisation Techniques</i>	167
7.6.9 <i>Comparing land Use and Visibility in the ALS visualisations</i>	168
7.6.10 <i>Assessing Feature Degradation</i>	169
7.7 <i>ALS Data Results (Upavon)</i>	171
7.7.1 <i>Introduction</i>	171
7.7.2 <i>ALS Resolution and Accuracy</i>	171
7.7.3 <i>Assessing the Accuracy of the Archaeological Feature Buffering</i>	172
7.7.4 <i>Assessing the Accuracy of the LRM Model</i>	174
7.7.5 <i>Summary</i>	175
8 Results – Integrated Datasets	176
8.1 <i>Introduction</i>	176
Combining Data from Multiple Sensors	177
8.2 <i>Digital Data Combination</i>	177
8.2.1 <i>Introduction</i>	177
8.2.2 <i>Raster Mathematics</i>	177
8.2.3 <i>Brovey Transformation</i>	179
Integrating Ground Based Data	183
8.3 <i>Introduction</i>	183
8.4 <i>Archive Weather Data (Everleigh and Upavon)</i>	183
8.4.1 <i>Average Rainfall</i>	183
8.4.2 <i>Soil Moisture Deficit</i>	184
8.5 <i>Geophysical Survey (Upavon)</i>	185
8.5.1 <i>Gradiometry Survey</i>	185
8.5.2 <i>Earth Resistance Survey</i>	187
8.6 <i>Soil Sampling</i>	188
8.7 <i>Correlation of Soil Moisture and ARS data</i>	189
8.7.1 <i>Correlation of ARS Data</i>	191
8.7.2 <i>Correlation of Soil Moisture and Hyperspectral Data</i>	192
Comparing Feature Detection Across the Archive ARS Sources	195
8.8 <i>Multi-Sensor Analysis of the Everleigh Study Area</i>	195
8.8.1 <i>Introduction</i>	195
8.8.2 <i>Comparison of Average Percentage Feature Length (APFL)</i>	195
8.8.3 <i>Comparing Feature Type and Visibility Across the Data Sources</i>	196
8.8.4 <i>Cross- Data Comparisons</i>	198

8.8.5 Comparing Uniqueness	200
8.8.6 Feature Certainty	201
8.9 Comparison of 'Traditional' vs 'New' visualisation techniques for ARS (Everleigh)	202
8.9.1 Introduction	202
8.9.2 Comparison of 'Traditional' vs 'New' techniques for Areas A/B and C	203
Summary of Results	206
8.10 Meeting the Objectives	206
8.10.1 Objective 3 – Assessing the Relative Value of ARS data	206
8.10.2 Objective 4 – Understanding Environmental Conditions	207
8.10.3 Objective 5 – Deriving Quantitative Information from ARS	207
8.10.4 Objective 6 – Applying 'New' Techniques	207
8.10.5 Objective 7 - Spectral Sensitivity	208
8.10.6 Objective 8 – ALS Visualisation Techniques	208
8.10.7 Objective 9 – ALS Model Accuracy	209
8.10.8 Objective 10 – ALS Intensity	209
8.10.9 Objective 11 – Comparison of Ground Geophysical Techniques and ARS	209
8.10.10 Objective 12 – Digital Integration of ARS Data	210
9 Discussion	211
9.1.1 Introduction	211
9.2 Digital Spectral Data for Archaeological Prospection	211
9.2.1 Introduction	211
9.2.2 Comparison to Other Sensors	211
9.2.3 Spectral Sensitivity	213
9.2.4 Seasonality	216
9.2.5 Visualisation Techniques	218
9.2.6 Integration with Ground Survey Techniques	219
9.2.7 The Contribution of the Salisbury Plain Study	220
9.2.8 Future Directions	221
9.3 ALS data for Archaeological Prospection	223
9.3.1 Introduction	223
9.3.2 Visualisation Techniques	224
9.3.3 Accuracy Assessment	226
9.3.4 Intensity	227
9.3.5 The Contribution of ALS to Airborne Multi-Sensor Survey	228
9.3.6 The Contribution of the Salisbury Plain Study	228
9.3.7 Future Directions	229
9.4 Developing Methods for Airborne Remote Sensing in Archaeology	230
9.4.1 Introduction	230
9.4.2 The Impact of Multi-Sensor Survey	231
9.4.3 The Impact of Multiple Visualisations	232
9.4.4 “High level” Integration of Data Sources	232
9.4.5 The Contribution of the Salisbury Plain Study	233
9.4.6 Future Directions	234
10 Conclusions	235
11 References	239
Appendix 1 – LRM Script	i
Appendix 2 – Geophysical Survey Report	i

Index of Figures

Figure 2.1: Schematic of how surface and subsurface archaeological features affect plant growth (after Beck 2009, AARG Teaching Resource).....	29
Figure 2.2: Electromagnetic spectrum reproduced from Lillesand et al 2009:5).....	29
Figure 2.3: Schematic of Light reflectance from a leaf structure (credit Jeff Carns: http://missionscience.nasa.gov/ems/08_nearinfraredwaves.html).....	31
Figure 2.4: The spectral response of healthy and stressed vegetation (data courtesy of USGS spectral library).....	31
Figure 2.5: Schematic of multiple returns of Airborne Laser Scanning data, where (a) represents discrete pulse (b) represents waveform and (c) represents full-waveform (reproduced from Beraldin et al. 2010:29).....	41
Figure 2.6: Illustration of strip height differences between flightlines with red areas indicating high error between flightline elevation values © TU OPALS, scale 1:25000.....	41
Figure 2.7: The twin probe earth resistance array (from Gaffney and Gater 2006:29).....	49
Figure 2.8: The passage of electrical current through the ground using a twin probe array from Gaffney and Gater 2006:30).....	49
Figure 4.1: Location map of the Salisbury Plain Study Areas.....	57
Figure 4.2: The Wiltshire Historic Environment Record for Everleigh Study Areas A and B.....	62
Figure 4.3: The Wiltshire Historic Environment Record for the Upavon Study Area.....	64
Figure 5.1: Simplifying Historic Environment Record symbology to better represent archaeological features.....	69
Figure 5.2: Assigning unique identifiers (UID) to features grouped by a single Primary Record Number (PRN) in the Wiltshire Historic Environment Record.....	70
Figure 5.3: True Colour Composite showing cloud obscuring archaeological features between flightlines.....	72
Figure 5.4: Archive airborne remotely sensed data coverage for the Everleigh Area.....	75
Figure 5.5: Everleigh Sample Areas A, B and C location map.....	76
Figure 5.6: Upavon study area location map.....	77
Figure 5.7: Area of ALS data collection, Upavon.....	79
Figure 5.8: Upavon ground survey location map, Site 1 (Coombe Down Enclosures) and Site 2 (Lidbury Camp).....	81
Figure 5.9: Upavon Field Site 1, Coombe Down Enclosures as recorded from the archive aerial photograph transcription (Wiltshire Historic Environment Record).....	82
Figure 5.10: Geophysical survey of Upavon Field Site 1, Coombe Down Enclosures looking south-west, illustrating the lack of visible topography over the area of the enclosures.....	83
Figure 5.11: Location of geophysical survey at Upavon Field Site 1 (Centred SU 1767 5222).....	83
Figure 5.12: Upavon Field Site 2, Lidbury Camp as recorded on the Wiltshire HER.....	85
Figure 5.13: The prominent outer bank and ditch of Lidbury Camp (Upavon Field Site 2) looking south-east.....	86
Figure 6.1: Flowchart illustrating the processing of airborne remotely sensed data and workflow for the study.....	90
Figure 6.2: Examples of the feature mapping exercise undertaken in this study.....	94
Figure 6.3: An example of true and false colour imagery in the Everleigh Study Area.....	97
Figure 6.4: An example of the imagery produced by the application of vegetation indices in the Everleigh Study Area.....	98

Figure 6.5: Examples of the processing techniques used for the archive spectral data in this study.....	100
Figure 6.6: Simplification of the processing stages to create a Local Relief Model	107
Figure 6.7: Profile of ground surface at the henge monument (SU 20645 52594 to SU 20716 52594). Location illustrated (top) and plotted (bottom).....	108
Figure 6.8: Location of the Ground Control Point profile over Lidbury Iron-Age Camp (shown overlaying the ALS LRM model).....	110
Figure 6.9: Location of weather stations with respect to the Salisbury Plain study areas.....	113
Figure 6.10: Location of the geophysical survey at Upavon Site 1, Coombe Down Enclosures, (overlain with the NMP transcription from the Wiltshire Historic Environment Record).....	116
Figure 6.11: Location of auger survey, Upavon Field Site 1, Coombe Down Enclosures.....	117
Figure 6.12: Location of the ground control points surveyed with kinematic Global Positioning System.....	119
Figure 6.13: Location of the Ordnance Survey Base Stations used to correct the kinematic Global Positioning System survey data and their distances from the study site.....	120
Figure 7.1: Detail of spectral processing undertaken for each of the Everleigh Study Areas....	127
Figure 7.2: Land use mapping for the Everleigh Areas A, B and C (see section 6.5 for class definition).....	128
Figure 7.3: Percentage land use categories, Everleigh Study Areas A and B.....	129
Figure 7.4: Feature recovery rates by band in the January and May spectral data (red outline denotes the red-edge wavelengths).....	131
Figure 7.5: Average Percentage Feature Length in the January and May spectral data (Everleigh)	133
Figure 7.6: The number of features visible and not visible by land use from the spectral data.	135
Figure 7.7: The relative feature recovery rates from the true and false colour composites of the January and May spectral data.....	137
Figure 7.8: Relative feature recovery rates from the Principle Components Analysis and selected Principle Components Analysis of the January and May spectral data.....	139
Figure 7.9: Chart showing the relative feature recovery rates from the vegetation indices applied to the January spectral data.....	145
Figure 7.10: Relative feature detection rates from the vegetation indices applied to the May spectral data.....	145
Figure 7.11: Results of the Separation Index calculation across the Eagle / Hawk hyperspectral data.....	149
Figure 7.12: Spectral wavelengths with the highest separability (90th percentile).....	151
Figure 7.13: Spectral wavelengths most sensitive to all archaeological features in the study area (overlap of key regions from figure 7.12).....	151
Figure 7.14: Differential visibility of positive features (lynchets) between the SRI and MRESRI vegetation indices.....	153
Figure 7.15: Airborne Laser Scan intensity image, Everleigh.....	155
Figure 7.16: Images comparing the impact of the altitude of illumination on the visibility of archaeological features.....	156
Figure 7.17: Variation of illumination angle at 45° intervals in shaded relief models.....	157
Figure 7.18: Relative feature detection rates from Principle Components Analysis applied to the Airborne Laser Scanned shaded relief model.....	158
Figure 7.19: Profiles measured for the same transect for the original Digital Elevation Model (DEM), a shaded relief model and the first Principle Component (PC1) of the shaded relief models (with Max and Min values from the Digital Elevation Model	

highlighted).....	160
Figure 7.20: Number of archaeological features detected using Slope, Aspect and Curvature mapping.....	161
Figure 7.21: Relative feature recovery rates from Horizon View model applied to the Airborne Laser Scanned topographic data.....	162
Figure 7.22: Interpolation artefacts in the Horizon View model which resemble ridge and furrow earthworks.....	163
Figure 7.23: The interpolation artefacts in the Horizon View model profile compared with the Digital Elevation Model profile.....	164
Figure 7.24: Relative feature detection rates from Local Relief Models applied to the Airborne Laser Scan topographic data.....	165
Figure 7.25: Showing the profile of a bank and ditch feature in the original Digital Elevation (DEM) and the Local Relief (LRM)Models.....	166
Figure 7.26: Comparison of all Airborne Laser Scan visualisation techniques to the Historic Environment Record record in terms of percentage of total of features detected. . .	167
Figure 7.27: Comparison of Local Relief Model (LRM) profiles for lynchet feature in an area of scheduled monument protection (Profile A) and heavy ploughing (Profile B).....	170
Figure 7.28: Comparison of Local Relief Model histograms for positive and negative features (as defined from the Historic Environment Record)	173
Figure 7.29: Comparison of slope from the Ground Control Point (GCP) data, Digital Terrain Model (DTM) and Local Relief Model (LRM).....	174
Figure 8.1: The result of combining the Principle Component 1 of the January spectral data with the Digital Elevation Model.....	178
Figure 8.2: Feature visibility in the digitally combined LRM 9 and January PC1 raster compared with the contributing sources.....	179
Figure 8.3: Comparison of all Brovey transformations of the January spectral False Colour Composite bands 14, 7 and 3.....	180
Figure 8.4: Comparison of Average Percentage Feature Length for all Brovey transformations of the January spectral False Colour Composite bands 14, 7 and 3.....	181
Figure 8.5: Chart comparing Average Percentage Feature Length for the Brovey transformations of the May False Colour Composite data.....	182
Figure 8.6: Average rainfall for the Salisbury Plain area.....	184
Figure 8.7: Relative location of geophysical survey data (figures 8.8-8.11).....	185
Figure 8.8: Gradiometry survey of Upavon Field Site 1 (SU 177 522) overlaid with the Wiltshire Historic Environment Record.....	186
Figure 8.9: Detail of eastern enclosure bank (SU 177 522 Upavon Field Site 1) in gradiometry data with profile.....	186
Figure 8.10: The high resistance bank feature as shown in the 0.25m apparent resistivity survey (overlain with the Wiltshire Historic Environment Record).....	187
Figure 8.11: The 0.5m apparent resistivity survey (overlain with the Wiltshire Historic Environment Record).....	187
Figure 8.12: Location of soil moisture samples, Upavon Field Site 1, overlain on the 0.25m apparent resistivity survey.....	188
Figure 8.13: Percentage water content by dried weight for each category.....	189
Figure 8.14: Correlation coefficient of earth resistance data across the wavelengths recorded in the hyperspectral data (Upavon).....	192
Figure 8.15: Correlation coefficient of soil moisture measurements across the wavelengths recorded in the hyperspectral data (Upavon).....	193
Figure 8.16: Correlation of soil moisture compared with SI the hyperspectral data (Upavon). ..	194

Figure 8.17: Everleigh Study Areas A, B and C location map.....	202
Figure 8.18: Percentage feature recovery for Areas A and B (using traditional techniques) compared with both traditional techniques and all techniques for subset Area C...	204

Index of Tables

Table 2.1: Basic specification of the most common airborne spectral sensors	30
Table 2.2: Vegetation Indices	35
Table 5.1: Archaeological Resources for the Salisbury Plain Study Area	67
Table 5.2: Airborne Digital Data Sources for the Everleigh Study Area	70
Table 5.3: Wavelengths of the vegetation bandset of the digital spectral data supplied for the Everleigh study area	72
Table 5.4: Wavelengths of the channels recorded by the 4-band vertical aerial photography. ..	74
Table 5.5: Airborne Digital Data Sources for the Upavon Study Area	78
Table 5.6: Field survey data collected for the Upavon Site 1, Coombe Down Enclosures	82
Table 6.1: Summary of Objectives covered by each method section	88
Table 6.2: Summary of software selected for each stage	89
Table 6.3: Attributes recorded for each feature in the Everleigh area	92
Table 6.4: Attributes recorded for each feature in the Upavon area	93
Table 6.5: Land use categories used for the Everleigh study area	96
Table 6.6: The visualisation models applied to the Airborne Laser Scanned data	104
Table 6.7: Workflow for the creation of a Local Relief Model, after Hesse 2010	106
Table 6.8: Datasets used for the correlation analysis	122
Table 6.9: Simplification of feature type categories for chi-squared analysis	124
Table 6.10: Table showing the groupings of data for Friedman's ANOVA	125
Table 7.1: Table showing relative feature recovery rates from the 4-band vertical aerial photography (total features numbers in brackets)	129
Table 7.2: Relative feature recovery rates from the archive spectral data (January and May 2001), Everleigh Area C	131
Table 7.3: Friedman's ANOVA ranking for percentage recovery of Average Percentage Feature Length from the January (J_) and May (M_) archive spectral data (Everleigh) . .	133
Table 7.4: Detailed explanation of land use categories used in the Everleigh area.	134
Table 7.5: Number of unique features in the digital spectral data	137
Table 7.6: Variation represented by the Principle Components Analysis of the Everleigh spectral data.	138
Table 7.7: Cross tabulation of features detected between the 14 band Principle Components Analysis, selective Principle Components Analysis, False Colour Composite and Band 8 of the January spectral data.	140
Table 7.8: Detail of features not mapped by the 14 band Principle Components Analysis of the January spectral data (where 0 denotes not present, 1 present)	140
Table 7.9: Cross tabulation of features detected between 4 band Principle Components Analysis, selective Principle Components Analysis, False Colour Composite and Band 8 of the May spectral data.	141
Table 7.10: Detail of features not mapped by the 14 band Principle Components Analysis of the May spectral data (where 0 denotes that the feature was not found)	141
Table 7.11: Friedman's ANOVA for the Average Percentage Feature Length in the January spectral data True Colour Composite, False Colour Composite and Principle Components Analysis	142
Table 7.12: Friedman's ANOVA for the Average Percentage Feature Length in the May spectral data True Colour Composite, False Colour Composite and Principle Components Analysis	142

Table 7.13: Cross comparison table of the vegetation indices applied to the January spectral data showing number of extra features mapped per index compared with with best performing visualisation methods	146
Table 7.14: Cross comparison table of the vegetation indices applied to the May spectral data showing number of extra features mapped per index compared with with best performing visualisation methods	146
Table 7.15: Scoring of vegetation indices for January and May based on uniqueness (compared to 14 band Principle Components Analysis and single best performing band) and total number of features visible.	147
Table 7.16: Issues with the original Separation Index and the resolutions applied as part of this study	148
Table 7.17: Mean and Standard Deviations for the four categories of features assessed with the Separation Index	149
Table 7.18: Separability Index as applied to selected vegetation indices	152
Table 7.19: Number of features mapped for each angle of illumination east of north on the ALS shaded relief models.	156
Table 7.20: Number of features not recorded by the Principle Component transforms	158
Table 7.21: Average Percentage Feature Recovery in the Principle Components Analysis of the shaded relief images	158
Table 7.22: Average Percentage Feature Length from the Horizon View images	162
Table 7.23: Count of features unique to each Airborne Laser Scan visualisation technique . .	168
Table 7.24: Combination of multiple Airborne Laser Scan visualisation techniques	168
Table 7.25: Combination of multiple visualisation techniques	168
Table 7.26: Summary of chi-squared analysis of feature visibility in the ALS visualisations	169
Table 7.27: Summary of the resolution of the bespoke Airborne Laser Scan data, Upavon Study Area	171
Table 7.28: Statistical summary of the planned ALS data, Upavon	172
Table 7.29: Root Mean Square Error (RMSE) between Airborne Laser Scanned models and Ground Control Point data	175
Table 8.1: Table showing percentage recovery of predicted features from the Brovey transformations of the January False Colour Composite data	180
Table 8.2: Table showing percentage recovery of predicted features from the Brovey transformations of the May False Colour Composite data	182
Table 8.3: Soil moisture content as measured in the cores	188
Table 8.4: Spatial auto-correlation of the Airborne Remote Sensing data	190
Table 8.5: Correlation of soil and Airborne Remote Sensing data	190
Table 8.6: Cross-correlation of Airborne Remote Sensing and Earth Resistance data	191
Table 8.7: Results of the Friedman's ANOVA ranking the remotely sensed data sources by Average Percentage Feature Length	195
Table 8.8: Results of the chi-squared analysis for feature type and visibility across all data	197
Table 8.9: Previously known and total features mapped by combining visualisation techniques and sources	199
Table 8.10: Number of unique features detected in each data set (4-band vertical aerial photography shortened to AP (All))	200
Table 8.11: Table showing the number of features mapped in multiple data sources	201
Table 8.12: Table showing the number of features recovered from each of the study areas. .	203
Table 8.13: Cross comparison table showing the number of features recovered by any two sources	205

1 Introduction

Britain's historic environment is subject to many pressures which threaten its survival in the 21st Century and increasingly those who curate it are being asked to consider entire landscapes when providing professional consultation. Work at Stonehenge (Parker Pearson et al. 2006) and Heslerton, in the Vale of Pickering, (Powlesland 2006) has shown the success of investigating the spaces between well known, visible remains. Progress has been made in determining the historic value of distinct landscape areas through targeted research projects and measures like Historic Landscape Characterisation. However, the site-based data which typifies the archaeological record and underlies many landscape assessments poses academic and prosaic problems. How is one to judge the significance of a landscape, to decide what is to be preserved and what can be aid to waste, when so much remains unknown about the nature of past human interaction with it?

The search for efficient ways to capture data at a landscape scale is driven by the need to record, understand and preserve our heritage before the pressures of intensive agriculture, resource extraction, settlement expansion, land use and environmental change remove it for good. To an extent this drives innovation with archaeology having a long tradition of adapting technologies developed in other disciplines to use them for archaeological prospection. This can be seen in almost any common survey technique from aerial photography to the geophysical techniques of earth resistance survey, magnetometry and GPR, and on into the widespread use of geospatial systems and software. However there are two technologies, digital spectral data and airborne laser scanning (ALS), that have begun to find their way into the archaeological landscape researcher's toolkit that offer the potential for a revolution in the way that sites are both prospected and recorded from the air.

One of the greatest difficulties with the adaptation of a technology to a new discipline is the lack of researchers with both the archaeological and technological specialism to evaluate the potential and pitfalls of the novel application. Once the technology has been demonstrated to detect archaeological features, as is the case with both digital spectral data and ALS, there is usually a period of where increasing numbers of applications of the technology are made without evaluation of its suitability or indeed its full potential.

This study was borne from just such a period in the use of airborne remote sensing (ARS) technology in archaeology. As will be illustrated in the literature review (2.3-2.5), although the use of digital spectral data and ALS data were becoming more commonplace in the first decade of the 21st century, there were still many unanswered questions around how to apply them

effectively to archaeological research. A systematic, quantitative and comparative study was required to look at a range of processing and visualisation techniques for ARS data enabling more effective application of the sensor technology. This research seeks to fill the gaps in our understanding of how to make full use of ARS data content and in doing so contribute to improved specification, methods and analysis in the future.

Aerial Survey – Identifying the Gaps

For more than a century, since the iconic capture of an aerial image of Stonehenge from a balloon in 1906, archaeologists have sought to fill the gaps in our understanding of historic landscapes using aerial survey. Time and again the remains of past human endeavours have been transcribed, predominantly from panchromatic oblique photography, to dramatic effect revolutionising our view of the historic environment. So effective is this technique for identifying previously unknown sites that it has spurred intensive national projects to review all archive photography, such as English Heritage's National Mapping Programme. In addition to illustrating the extent of upstanding features, aerial archaeologists soon discovered that a feature need to be visible above ground to be recognised. Proxy in changes in soil and vegetation growth, commonly referred to as soil and crop marks indicate not only the presence of archaeological features but their active destruction by intensive agricultural regimes.

Sites identified through aerial or field survey are recorded not necessarily because they are the most significant but because they are visible to researchers in some way. The nature of the evidence upon which archaeologists base their research and professional judgements is heavily biased towards remains which are both topographically distinct from their surrounding environment and visible either on the ground or in aerial photographs. As a long-standing technique, the temporal, vegetation, soil type and observer biases of aerial photographic survey are well documented (Wilson 2000; Cowley et al 2010; section 2.2). Consequently there is a requirement to look to other ARS techniques to begin to close some of the gaps left by aerial photographic survey. In essence there is a need to increase the range of features that are visible to surveyors and to try to reduce the dependence on “ideal” temporal, vegetation, rainfall and illumination conditions for survey by employing different ARS techniques and a more holistic approach to survey data analysis.

Evidence from other environmental disciplines and from a number of successful archaeological applications to date indicates that recording the non-visible spectral properties of an archaeological feature using digital spectral data and accurately measuring microtopography using ALS can improve detection and interpretation. These have shown that through the application of improved sensor technology it is now possible to record remotely more aspects of

the historic environment than by using aerial photography alone, while retaining the landscape-scale overview that is critical for heritage management.

In principle, the ability of remote sensing techniques, such as airborne laser scanning (ALS) and airborne digital spectral imaging, to significantly enhance our understanding of archaeological features within a landscape is clear. ALS allows greater and more precise measurement of the topography of the ground surface than any other technology at landscape scale, while airborne digital spectral imagery captures the nature of vegetation and soil changes in not just the visible wavelengths but also in the near and short-wave infrared (NIR and SWIR) and thermal regions of the spectrum. Indeed a plethora of recent survey applications, particularly of ALS data, have shown the value of the tool for the detection of new features of archaeological interest (Shennan and Donoghue 1992; Bewley et al. 2005; Winterbottom and Dawson 2005; Devereux et al. 2005; Crutchley 2006; Powlesland et al. 2006). However, as with many methods borrowed from geographic or environmental sciences, there is a sense that archaeologists have yet to utilise the full information content that ALS and airborne digital spectral data can provide about archaeological features, relying heavily on the expertise of remote sensing specialists trained in other disciplines to process the data.

While it is relatively easy to demonstrate archaeological feature detection via the application of a high resolution airborne laser scanner, few have rigorously examined the impact of the processing and visualisation of these data in a quantifiable way. Likewise, digital spectral images are invariably analysed without prior assessment of wavelength sensitivity or understanding of the physical and biological processes that underpin spectral response (as shown by Evans and Jones 1977; Riley 1980 and Hejcman and Smrz. 2010). Too often airborne sensors are used in isolation from each other, reducing the breadth of feature data that is collected. It was recognised at the inception of this project that the real power of airborne sensors lies in their complementarity, with multi-sensor survey providing a raft of new possibilities that have the potential to revolutionise our understanding of archaeological landscapes.

It was also felt that the weight of previous study had been devoted to one landscape type – alluvial valleys. In many respects this was a direct consequence of both the sources of funding and ARS data available to researchers¹. Most of the areas where ARS for archaeological prospection had been applied prior to this study were under intensive arable cultivation. While undoubtedly this land use is of high importance for archaeological research as it has a direct,

¹ The Aggregates Levy Sustainability Fund (ALSF) provided the financial support for many early projects using ARS in archaeology while the Environment Agency of England and Wales (EA) holds the largest archive of data (section 2.4.1).

negative impact on archaeological feature preservation, it was recognised that in temperate regions such as the UK, arable cultivation only accounts for c.25% of land cover (Morton et al. 2011, section 4.2). In contrast the application of ARS for grass-dominated environments, which account for almost 40% of land cover in the UK has been almost entirely overlooked. Such regions provide a niche environment lying at the margins of sustainable agriculture, between the arable-dominated lowlands and the moorland of the higher altitudes. These areas contain a wealth of information about changing subsistence strategies through the prehistoric and historic periods as they are more readily affected by changes in climate. They provide evidence for previous landscape interaction that is less affected by deep ploughing. However due to the low detectability of crop and soil marks in the hardier vegetation of these regions using traditional aerial techniques, archaeological features may be harder to locate, particularly if a multi-sensor approach is not used.

Consequently, this study focusses on an extensive area of grassland renowned for the range and preservation of its historic landscapes, and the quality of previous archaeological research – Salisbury Plain, Wiltshire, UK. By using an area where intensive study using traditional airborne and ground based techniques has already lead to an extensive record and understanding of archaeological landscape features, it will be possible to provide a robust baseline for the comparison of new techniques and quantitative analysis of their contribution to landscape research.

The contribution of this study to current knowledge

This thesis presents the work undertaken in fulfilment of a three-year doctoral study, investigating processing and analysis techniques for airborne remotely sensed data that are specifically designed to maximise the usefulness of such sources for understanding archaeological features in non-arable areas. So little prior work had been undertaken to investigate the individual capabilities of ALS and digital spectral sensors with regard to archaeological research that a comprehensive analysis of each data type had to form the starting point of this multi-sensor analysis. By undertaking the first systematic analysis of airborne ALS and airborne digital spectral data in combination with ground-based geophysics and soil moisture measurements for a site in the UK, it was hoped that a significant contribution to current understanding of how to apply these technologies could be made.

The main benefits of such a systematic approach will be the first direct comparison between a number of different ARS datasets, the aerial photographic archive and ground observations for a grass dominated environment. The study will begin by employing methods for archaeological feature transcription used by the National Mapping Programme for aerial photography and data

visualisation techniques common to environmental remote sensors grounding the study in techniques that are well understood. The research will then look at novel methods for incorporating ancillary data to aid our understanding of the patterns of feature detection, building on the experimental design of previous studies to target gaps in our methodological and technical understanding. Using the knowledge gained from this study, it will be possible to give further insight about data sources, visualisation techniques, transcription methods and other forms of feature detection that will be of general use to the growing community of airborne remote sensing specialists and will illustrate the value of multi-sensor ARS for grass-dominated landscapes to the wider historic environment profession.

This document begins with a review of the academic literature and context to the study (Chapter 3), followed by a summary of the aims and objectives of the research (Chapter 2), from which the aims and objectives of the work were derived. Chapter 4 introduces the Salisbury Plain study areas of Everleigh and Upavon, detailing the rationale for the choice of sites, relevant previous investigations. Following on from this Chapter 5 gives details of the archive ARS and archaeological data used in the Everleigh study, along with the planned ALS and hyperspectral data acquisition for the Upavon area. The methods used to assess these data are given in Chapter 6. The results of the study are given in Chapters 7 and 8, while Chapter 9 discusses the implications of the project's findings for the archaeological application of airborne remote sensing data and directions for future research. Chapter 10 gives the conclusions of the work, followed by the Chapter 11 and the Appendices which give supporting documentation including references, the processing script used to calculate the Local Relief Model and a full geophysical survey report.

2 Literature Review

2.1 Introduction

The purpose of the review of current literature was to identify the gaps in current understanding regarding the use of ARS for archaeological research and to identify potential method areas for the project. The results of the review are presented here with two themes that link directly to the research objectives laid out in Chapter 2. Sections 2.2 - 2.7 describe the current status of research into the archaeological application of airborne remote sensing (ARS) data and identify the potential value that ARS data can add to archaeological survey (in fulfilment of Objective 1). Sections 2.9 - 2.11 comprise the technical literature review giving specific details of each of the data types used in the study, and appropriate processing techniques (in fulfilment of Objective 6).

Remote Sensing for Archaeology

2.2 Archaeological Remote Sensing Techniques in Context

The term “archaeological remote sensing” in its broadest application covers the techniques that allow an observer to detect evidence of features that indicate past human engagement with the landscape. The term commonly incorporates not only airborne remote sensing (ARS) techniques, which are the main focus of this project, but also satellite data and geophysical survey, encompassing a multitude of different sensors that measure complex and often subtle changes in the land surface and beneath the soil. Whatever the technique employed, the central tenet of remote sensing is that target features will contrast from their surrounding matrix in a measurable way (Beck 2007). For archaeological features, these differences can be categorised into two groups; *direct effects*, where the feature itself can be measured e.g. the changes in topography associated with bank and ditch features; and *proxy effects*, where a sub or near-surface feature causes a localised change in soil or vegetation properties, e.g. crop marks.

ARS is extremely important to the discipline of archaeology, allowing non-invasive detection and mapping of features at a landscape scale. This data underpins both academic research and heritage management, allowing professionals to quantify and respond to threats to the historic environment. However the weaknesses of colour or monochrome aerial photography, which has been the main source of ARS data for almost a century, have been well documented (Wilson 1975; Cowley 2002; Brophy and Cowley 2005). The appeal of other ARS techniques, such as airborne laser scanning (commonly referred to as lidar) and digital spectral imaging (also known

as multispectral or hyperspectral imaging), lies in great part with their ability to replicate and complement the established tools of archaeological landscape analysis, bridging some of the gaps in current understanding. Sections 2.2.1 and 2.2.2 detail traditional methods for identifying the changes typical of archaeological features and how “new” ARS techniques can complement these.

2.2.1 Detecting Direct Effects

When detecting direct changes caused by human interaction with the landscape, two methods are generally employed: walkover survey and aerial photography. Both of these techniques, although commonly used, have distinct disadvantages for survey of large areas. Walkover survey is defined as the technique of surveying in transects to record archaeological features and can be undertaken with or without concurrent artefact collection (as per Fulford et al. 2006; RCHAMW 2009). This type of survey is time consuming, may be restricted by vegetation or land use and is limited to identifying features with noticeable upstanding remains or artefact scatters caused by plough damage (Fulford et al. 2006). In addition it is often difficult to view the evidence for an entire landscape from any single point within it, which can lead to difficulty in producing a synthesised and holistic assessment. Even during the process of detailed metric survey, the bias of both what is visible to the surveyor and the amount of visible evidence that is interpretable from their near-surface perspective, plays a key role in the final interpretation (Doneus and Briese 2006).

By contrast, oblique aerial photography, especially in raking light (defined by Wilson (2000) as a sun angle of no more than 20° above the horizon) can be used to identify features with upstanding topography in their wider cultural and natural environment. Often this technique is more effective than observations from ground level, especially if the remains are slight or the site covers an extensive area (Bewley 2001). Aerial photography is one of the most widely used, and best understood, methods of prospection and recording of archaeological sites (Horne 2011).

There are some issues to be considered when translating the evidence of oblique, raking light, photographs into accurate spatial records of the archaeological features depicted. Firstly those features which run parallel to the direction of light will have little or no presence in the image. While this could be overcome to an extent by repeat acquisition of photographs at varying times of year, this is both impractical and logistically impossible if the sun is the only illumination source. The second issue occurs when trying to locate the features seen in oblique photography. This is particularly a problem in uncultivated and coastal areas where lack of ground control features can render precisely locating the features identified impossible. Finally, and most

obviously, it is not possible to record features that are obscured by vegetation or shadows .

Airborne laser scanning (ALS) (which operates on a principal of light detection and ranging, or lidar) has the potential to redress some of the weaknesses of the established landscape survey techniques with regard to detecting direct changes in the landscape. The high accuracy digital terrain and surface models (DTM and DSM respectively) that can be rendered from ALS enable the identification of topographic features and can be shaded artificially from any angle or azimuth to replicate optimum illumination conditions (Devereux et al. 2008). In addition the data can be filtered to remove vegetation such as forest canopies, allowing the recording of the ground surface beneath (Devereux et al. 2005). Although expensive, it has been calculated that the cost of collecting airborne data is less than the equivalent cost of a walkover survey team and is far more effective in some landcover types, e.g. forested areas (Crow et al. 2007). As coverage of the landscape can be total, using an ALS-derived DSM can also enable more efficient deployment of ground survey teams to targeted areas. For these reasons, since 2005 the growth in the use of airborne laser scanning for archaeological prospection has been tremendous, driven in large part by the results of research in the Trent Valley, funded by the Aggregates Levy Sustainability Fund (ALSF). This is discussed in more detail in section 2.4.

To date, the majority of projects using ARS techniques, including surveys at Stonehenge and the Loughcrew Landscape project (Shell 2005; Bewley et al. 2005) have used the digital surface models (DSM) created from ALS for prospecting and mapping new features or landscapes. Recently, an increasing number of case studies using ALS-derived models to identify previously unknown features have been published (Bock et al. 2008; Challis et al. 2008c; Corns and Shaw 2009; Millard et al. 2009; Charlesworth et al. 2010; Sittler and Heinzl 2010; Chase et al. 2011). Throughout this review of published and grey literature the emphasis is on those projects that have contributed to progressing analysis techniques and technical understanding of how ALS data can be used to investigate archaeological features, rather than the improvement in archaeological understanding brought about by simply applying a high resolution terrain model to an area that was previously not recorded in 3D. Projects in the former category provide a better context to the analytical research being undertaken for this study.

2.2.2 *Detecting Proxy Effects*

Aerial photography is also the primary technique used to identify features which have no upstanding traces but are typified by near-surface changes in soil moisture content and vegetation composition (Wilson 2000:53). However the identification of these features relies heavily on the differences in contrast between the material and structure of an archaeological feature and that of its surroundings and/or the impact of this contrast on the structure and

growth of vegetation. Additionally, variance of this kind is generally only visible under certain conditions, limiting the time of acquisition and making aerial photographs far less useful over pasture and uncultivated land. It has long been recognised that aerial photographs only capture records of such features in specific circumstances and the visibility of crop and soil marks from the air is heavily affected by underlying soil type and geology, vegetation, agriculture and seasonal variance (Brophy and Cowley 2005). This leads to biases in the information gathered from aerial photographs that must be considered when using this technique as the basis for holistic landscape survey (Cowley 2002).

A key tenet of the biological study of vegetation stress is that the near infrared (NIR) region of the spectrum is particularly sensitive to plant mass and health, more so than the red, green, blue reflectance of the visible spectrum (Lillesand et al. 2008). As such it has been postulated that this region of the electromagnetic spectrum may enable the improved recording of archaeological crop mark features, thus potentially reducing the impact of some of the inherent biases of geology, land cover and timing of acquisition that affect standard aerial photography (Beck 2011). The majority of aerial photographs used for archaeological research only capture visible wavelengths and, due to the historic cost of processing colour film, its instability as a long term storage format and difficulties of ensuring good exposure, monochrome panchromatic film has been preferred for archive photography (Gumerman and Lyons 1971; Wilson 2000). This means that specific record of the NIR reflectance of archaeological features is mostly absent from the aerial archive. However, there has been some use of infrared wavelengths to map archaeological features, most frequently using modified cameras and colour infrared (CIR) film (Edeine 1956; Strandberg 1967; Agache 1968; Gumerman and Neely 1972; Hampton 1974; Verhoeven 2008). This body of research illustrates the value of the non-visible wavelengths for identifying anomalies caused by differing vegetation conditions, but is confined by the limited spectral range of the sensor and a general misperception of the nature of electromagnetic energy (Verhoeven 2008).

In contrast to standard CIR photography, digital spectral imaging (commonly referred to as multi or hyperspectral imaging) captures the breadth of the electromagnetic spectrum, including the NIR region, by the acquisition of dozens to hundreds of contiguous spectral bands. Despite first being used to detect archaeological features in the UK over 20 years ago (Donoghue and Shennan 1988) and showing some promise both in the UK and abroad (Donoghue and Shennan 1988; Winterbottom and Dawson 2005; Powlesland et al. 2006; Traviglia 2006), uptake of airborne spectral sensors has been limited. Conversely during this time there has been a rise in the use of spectral data recorded by satellite platforms for archaeological survey (Parcak 2009:23-41 provides a full summary of this topic). In section 2.3, previous applications of

digital spectral imagery for archaeological prospection are discussed further, along with their implications for the current study.

2.3 Digital Spectral Imaging in Archaeological Research

2.3.1 *Introduction - Exploring the Invisible*

Although modern digital spectral sensors were first used for archaeological prospection in the late 1980s, the first experimentation with multispectral imaging for identifying crop mark features in the UK was undertaken by a team from the Royal Commission on Historical Monuments England and the University of Pennsylvania in 1970 (Hampton 1974). For this study the multispectral sensor comprised four 70mm F95 cameras recording panchromatic, colour and NIR across wavelengths from ~390nm to ~900nm (Hampton 1974:38). Various filter combinations were used on the panchromatic films to isolate, yellow, orange, blue and green wavelengths in a survey of four sites that was repeated four times between June and August, the peak crop mark season. The survey is notable for its attempt to deconstruct which wavelengths were contributing most to the visibility of crop mark features at each site for each period, although as the filters and films varied, the data from each sortie is not precisely comparable (Hampton 1974:40). The site of greatest interest to the current research was Willesley Warren, a site of mixed period occupation (Neolithic - Roman) situated on chalk downland, covered by a variety of crops in the year of survey (grass ley, pasture, spring barley and winter wheat). The false colour NIR film was found to perform well over the areas of cultivation in June and July, but in the areas of grass the NIR was most useful later in the season. Overall the results indicated that the combination of NIR and panchromatic imagery would record most anomalies. The real advantage of the system trialled in this research was the complementarity of the sensors, resulting in more features recorded in any combination of cameras (and therefore wavelengths) than by a single sensor. However the complexity of predicting the best filters for each land cover and geology was also highlighted illustrating the requirement for detailed work on spectral sensitivity.

Verhoeven (2011) provides an excellent summary of the conduit of NIR research in archaeology in the years since the publication of Hampton's work, citing more than 25 projects that have noted the advantages of using non-visible wavelengths captured using a variety of platforms (including conventional colour infrared photography, airborne or satellite multispectral imagery). However many of these observations were not made in a systematic or rigorous way as, for the most part, contemporary colour imagery was not available for comparison (Verhoeven 2011). Of the projects that could make comparisons, almost all were based on

standard colour versus colour infra red (CIR) film rather than digital spectral data. This led to a lukewarm reception by archaeologists for the CIR imagery which was awkward to use, (requiring more skill than standard imagery to expose), performed poorly in weak light conditions (Buettner-Janusch 1954) and was difficult to process consistently (Benton et al. 1976). In addition CIR film has low spectral clarity as the NIR sensitive band also samples large portions of the visible spectrum (Verhoeven 2011). Results of recent work have shown that digital cameras, modified to record the NIR region, remove many of these issues and provide consistent results in comparison with colour imagery (Verhoeven et al. 2009).

Work using NIR photographs has provided a proof of concept for the use of broadband, very near infra red wavelengths for identifying archaeological features, but questions remain as to how to define the spectral response of proxy vegetation features and to relate this to changes in season, soil moisture and ground cover (Verhoeven 2011). Additionally, building on work in the environmental disciplines (see section 2.10), there is scope to extend the study of non-visible wavelengths to features typified by changes in soil composition rather than vegetation change. Both these research directions require sensors that are more spectrally sensitive than NIR photography, covering both a wider range of wavelengths and greater spectral definition.

The most abundant source of more detailed spectral information can be garnered from satellite imagery. While at one time satellite data was viewed as too poor in both spatial and spectral resolution to be of use to archaeologists (Parcak 2009:34), this view has been overturned as the specification of satellite sensors has improved and high quality military satellite data is declassified. Studies have shown the value of both modern and archive satellite imagery for archaeological research (Mumford and Parcak 2002; Campana 2003; Lasaponara and Masini 2005; Lasaponara and Masini 2006; Beck et al. 2007; Cavalli et al. 2007; De Laet et al. 2007; Donoghue et al. 2007a; Lasaponara et al. 2007; Lasaponara et al. 2008; Nuzzo et al. 2008). However despite some publications by Cox (1992) and Fowler (2002) there has been little use of satellite imagery for archaeological research in the UK. Aside from the issue of coverage, the spatial and spectral resolution of satellite imagery is better suited to large scale features that provide distinct soil differences from their surroundings such as the Tell settlements of Syria (Beck et al. 2007; Donoghue et al. 2007a). Although spatial resolution has improved, satellite spectral resolution is still limited to broad bands in the NIR, SWIR and Thermal, limiting more detailed analysis of the spectral characteristics of the archaeological features observed. For this reason, the current research will focus on the use of airborne multi and hyperspectral sensors (henceforth referred to collectively as digital spectral sensors), as they currently provide the best combination of spectral and spatial resolution for detailed feature analysis.

2.3.2 *Archaeological Applications of Digital Spectral Sensors*

As mentioned above, digital spectral imagery has received significantly less attention than airborne laser scanning in archaeological research to date in the UK, despite first being used to detect features over 20 years ago (Donoghue and Shennan 1988). In part this is due to the poorer spatial resolution of spectral systems (c.1-5m) but also to the lower availability of spectral datasets. For the sake of contiguity with the original publications the spectral sensors discussed below are referred to by their commercial names. Table 2.1 in section 2.10 provides a detailed breakdown of their key attributes.

The first landscape study to integrate multispectral data with established archaeological remote sensing techniques of magnetometry survey and the aerial photograph archive, was the Vale of Pickering Landscape Research Project. This project is one of the longest running archaeological research initiatives in the UK, with campaigns of aerial photography, excavation and geophysical survey over more than thirty years (Lyll 2006). As such it provided a wealth of ground and aerial observation with which to compare the remote sensing techniques. The two existing publications that report on the remote sensing aspects of the project focus on the overarching archaeological research objectives (Powlesland et al. 1997; Powlesland 2006). However technical details of the ARS analysis are included in James Lyall's MSc thesis (2006), in which the long-term airborne and ground-based survey are fully explained and analysed. The work undertaken by Lyall illustrates the complementarity of the multi-sensor survey, and as such provides a precursor to subsequent projects.

The method underlying Lyall's project was essentially qualitative, with images from each of the techniques processed and georeferenced before features of archaeological interest were polygonised and compiled into a geodatabase. However, the project did investigate the technicalities of multispectral and thermal survey as applied to archaeological prospection and the factors which might affect its success. Two sites were selected for detailed comparison of visible and infrared (VNIR), short wave infrared (SWIR) and thermal multispectral data. The airborne data were collected by the NERC ARSF using a Compact Airborne Spectrographic Imager (CASI) and Airborne Thematic Mapper (ATM) and were compared, along with magnetometry survey, against the existing air photograph archive. At each site the techniques were shown to be complementary, for example at one site, nine key features were detected by at least two techniques, whereas almost twice that number were only detected by a single technique (Lyll 2006: 151). Some analysis of the feature types was undertaken, illustrating that the biggest factor affecting the visibility of features in both the ATM and CASI data was the reduced ground resolution of the data (1.5m) compared with aerial photography (0.15m) and magnetometry (0.25m) (ibid:191). Another key factor which could have affected feature

identification in the CASI data (and by inference also the ATM data) was discovered almost by chance through the analysis of two flightlines for the same site. Although the flightlines were recorded only six minutes apart, the remains of a ladder settlement were visible in the first flightline but not the second (ibid:201). It was determined that when the features lay at the edge of the scan line of the instrument, early cropmarks, formed primarily by differences low down in the vegetation canopy, could not be identified in the more oblique image as only the top of the canopy was contributing to the recorded reflectance. It was concluded that early cropmark features are only visible in CASI data when the scan angle is close to nadir, giving a clear indicator for optimal instrument set up (Lyall 2006:85).

A further use of ATM data for a site in the UK was for the study of the visibility of buried archaeological features in areas of mobile sand on the Islands of Coll and Tiree off the north west coast of Scotland (Winterbottom and Dawson 2005). The study was important as it showed the potential for the examination of archaeological remains in a non-alluvial area using the ATM sensor, and the importance of iterative feedback from site visits for improving the interpretation process (Winterbottom and Dawson 2005: 213). However one of the main difficulties encountered in the more topographically varied areas of the study was distinguishing between archaeological features such as cairns and natural features with similar topography, such as sand dunes (Winterbottom and Dawson 2005:218). It is postulated that with the simultaneous collection of high resolution ALS data, the problems of differentiation between anthropogenic and natural features could have been simplified. The results of this research clearly highlight the limits of the spectral data as regards microtopographic analysis.

The studies discussed above indicated that prospection using wavelengths in the thermal region gives better results than using the VNIR wavelengths alone. To date, Kay McManus' doctoral study of airborne thermography (2003) is the only UK study to date to have examined in detail the relationship between remotely sensed data, vegetation attributes and corresponding shallow ground disturbance. Using the ATM, McManus investigated the possibility of using the thermal infrared response to model changes in thermal inertia (McManus 2003). It was hypothesised that shallow buried features of archaeological or geological origin would cause changes in the thermal radiation which could be measured from the airborne platform. The research applied theoretical models of thermal inertia to airborne data, concluding that it was not possible to calculate direct radiance from the airborne data and that apparent thermal inertia (ATI) modelling corresponded to temperature effects of the surface vegetation or very shallow features (at a depth less than 0.05m) rather than the characteristics of the more deeply buried features (McManus 2003:330). It was thought that the lack of correspondence of the radiance measure by the ATM and the surface temperature was due to miscalibration of the data evidenced by

seasonal variations to the radiance histograms of control areas (ibid: 254). Additionally, the timing of the day and night flights needed to be more precisely linked to the diurnal minimum and maximum temperatures of the soil column to optimise conditions for modelling.

As it was postulated that the amount of solar radiation emitted and reflected by the soil would be masked by the vegetation fraction throughout the year, one of the aims of the research was to understand the effect of vegetation on ground based monitoring of soil temperature and by inference on the reflectance recorded by the ATM. By monitoring ground temperatures at two sites, McManus was able to illustrate that solar penetration on the site dissipated between 0.2m and 0.5m below the surface, regardless of substrate properties, with temperatures at 0.5m below the surface showing no diurnal variance (McManus 2004:288). Diurnal patterns of maximum and minimum temperatures of the soil were detailed for sites under pasture and those under crop as the vegetation developed, with time ranges for acquisition recommended between 13.00-16.00 and 05.30-09.30 respectively for features at shallow depth. It was therefore noted that although the ATI could be a useful tool for identifying near-surface features in short grass or low crop, as the vegetation fraction increased the potential for identifying anomalies in the soil decreased.

Generally, thermal modelling was not found to give significant benefit over simpler visual and mathematical analysis of the data, especially given the more complicated process of georectification that the ATM demands (McManus 2004:337). It was also noted that not all geophysical techniques were suitable for corroboration of anomalies identified via the thermal data, as features picked up by each of the methods did not always correlate. With respect to the current research, McManus' work is useful in two key areas, i) the methodological approach of visual and mathematical analysis of the airborne data and ii) the complex relationship of vegetation cover to soil properties over the growth cycle. The conclusion that the anomalies viewed in airborne data bore little relation to sub-surface soil properties, but were dominated by vegetational effects and the surface of the soil, requires further consideration as it is generally assumed that the differential growth of vegetation or crop marks represent sub-surface features to a maximum depth of the crop root (0.3-0.75m) (Evans and Jones 1977). Clarifying the relationship between features identified in crop or pasture and the subsurface changes they represent is an area which requires work specific to the sites being investigated.

The most recent project in which a suite of specific processing techniques were systematically assessed was the 2008 review of multi and hyperspectral data supported by the ALSF (Challis et al. 2008b; Challis et al. 2009). The project took ATM and CASI multispectral and Eagle hyperspectral data for selected areas of the Trent Valley and trialled processing methods that are familiar tools employed in other remote sensing disciplines, such as colour composites, thermal

images, vegetation indices, tasselled cap transformations, principal components analysis and classification. The results of this study were promising but limited by what could be achieved with archive data (Challis et al. 2009). The ATM data were found to out-perform those collected using the CASI and Eagle sensors when identifying archaeological features. However, this conclusion should be regarded with caution as the CASI and Eagle data were far from optimal for the identification of archaeological remains, with the CASI data dating from 1996 and suffering severe geometric distortion that could not be corrected and the Eagle data being collected in the autumn season when the fields were under bare earth conditions. It was also considered that CASI data with a resolution finer than the c. 2m data used in this study would have greater potential, as would Eagle data collected when the study area was under crop (ibid, 74). No mention was made of the potential of using the Hawk sensor, which measures shortwave infrared (SWIR) that has a proven application for archaeological prospection (Winterbottom and Dawson 2005:218). In terms of the processing methods, the two selected vegetation indices (NDVI and Tasselled Cap) were observed to enhance visibility of archaeological features, but unlike Traviglia's work in Italy(2006; 2008), no effort was made to distinguish which indices were most appropriate to the vegetation encountered.

With respect to improved processing techniques, Cavalli et al. (2007) showed the potential for using specific indices to identify the most important parts of the spectrum for identifying buried archaeological features. This is an important consideration given the magnitude of spectral resolution in data collected by hyperspectral sensors such as Eagle and Hawk which collect data in the very near infra red (NIR) and short wave infra red (SWIR) regions respectively (2007:282). The study concluded that the archaeological information content derived by analysing the outputs of the image processing techniques is more significant than the information obtained by interpreting each single band and the available historical aerial photographs (Cavalli et al. 2007, 272). The most recent academic studies of airborne spectral data in the UK, (including the only known example of purpose-flown Eagle and Hawk sensors for the Hayton Landscape Project), were undertaken by doctoral researchers Ali Aqduş and Rachel Opitz. Both studies were submitted in 2009 to the University of Glasgow and Cambridge University respectively, but unfortunately remain unpublished and in the case of the Aqduş thesis embargoed until 2012. As such it is impossible to evaluate the processing techniques that were used although some success was reported using principle components analysis (PCA) and vegetation indices (Opitz 2009b; Aqduş and Hanson pers. comm. 2009).

To date there has been no attempt to apply the rigorous methods employed by Hampton (1974) and Traviglia (2008) to modern airborne spectral data for an archaeological landscape in the UK, where the temperate vegetation and lack of stone-built archaeological features differs

significantly from recent Mediterranean applications (Ben-Dor et al. 2001; Traviglia 2006; Rowlands and Sarris 2007). This has resulted in a lack of understanding of how spectral data could, and should, be applied for archaeological feature detection in the UK and has contributed to the lack of use of this data by the discipline. There is a pressing need for an improved understanding of the environmental, physical and biological properties that affect feature detection. This gap in current knowledge is reflected by the inception in 2010 of the AHRC and EPSRC council-funded project, Detection of Archaeological Residues using remote sensing Techniques (DART). This three-year project aims to collect ground-based and airborne data for four study sites (three arable and one pasture) in the UK to explore the factors that produce contrasts associated with archaeological features, how these contrasts vary over space and time and what sensors can best detect them (Beck 2010).

Although projects such as DART bring welcome recognition and investment to the field of digital spectral imaging for archaeology, they are not without limitations. Due to the complicated logistics and time-frames involved, projects can only give insight into a particular environment, geology and archaeological feature type over a limited period and so provide valuable but specific information that may prove difficult to up-scale either to the landscape level or to other landscapes. Additionally, although ground-based geophysical techniques will be employed, there is no consideration of the impact of topographic change as measured by ALS data as a contributing factor to the detectability of features. Therefore it is essential that rigorous multi-sensor research in this field continues in different environments, making full use of archive data in addition to bespoke acquisitions, in order to build the knowledge-base that will enable heritage professionals to make better use of spectral data and understand its relative contribution for archaeological feature detection when compared with other techniques.

2.4 Airborne Laser Scanning in Archaeological Research

2.4.1 Introduction

The remote sensing technique that has enjoyed the most attention in recent years is airborne laser scanning (ALS). Historic environment professionals have been keen to exploit the potential of the high resolution, high accuracy surface and terrain models that ALS can provide as resources for the visualisation and mapping of landscapes following the publication of the Stonehenge project results (Bewley et al. 2005). While the use of the data in this study was limited to shaded relief visualisations, with archaeological features mapped using standard National Mapping Programme (NMP) protocol, it can be viewed as a feasibility study recognising the value of ALS data to identify archaeological remains when compared with traditional aerial photographic inscription. Subsequent studies in the UK have focussed on two main research areas; the potential to record features beneath forest canopy (Devereux et al. 2005; Crow et al. 2007) and the modelling of alluvial valleys (Challis 2004; Oxford Archaeology North 2007) with the vast majority of work to date funded by the Aggregates Levy Sustainability Fund (ALSF).

One of the principle advantages of ALS over other airborne survey techniques is the ability to “see-through” the tree canopy to the ground surface beyond. This is because only a portion of the laser is reflected from the vegetation, (see 2.11 below) allowing the remaining backscattered reflections to be modelled as the ground surface and providing impressive insights into the archaeological landscape beneath forested areas (e.g. Crow et al. 2007; Gallagher and Josephs 2008; Bock et al. 2008; Charlesworth et al. 2010; Sittler and Heinzel 2010). The majority of published projects have been focussed on the recovery of previously unknown archaeological features rather than technical development of ALS technique, although Doneus and Briesse (2006) provide an exception to this generalisation.

2.4.2 ALS Research in Archaeology – The Aggregates Levy Sustainability Fund

Although there has been great excitement about the possibilities of ALS data for detection of features, with a handful of notable exceptions (often only available in the grey literature surrounding projects such as the Trent Valley Geoarchaeology Research (Challis 2004; Challis 2005a), there has been little detailed analysis of the processing of these data. Research in the UK to date has been undertaken mostly in a commercial context as part of the ALSF scheme, with attendant time, budgetary and scope restrictions, and with the focus on the interpretation of the images produced, not their derivation. This stems in part from the fact that the majority of ALS data used in archaeological studies is “second-hand”, having been acquired and processed

by the Environment Agency of England and Wales (EA) for hydrological and flood mapping purposes; very different purposes to those of the historic environment profession. At the present time there appears to be a heavy assumption by most in the historic environment sector who come into contact with ALS data that processing techniques and filters developed for hydrological mapping or environmental work are adequate for archaeological assessment, although this could be the consequence of a lack of opportunities and funding to explore the issue further. While Crutchley (2010) flags some potential pitfalls of using data processed for different purposes, there has been little discussion of developing more appropriate processing techniques, with archaeological prospection in mind from the outset.

The exception to this is the work of Keith Challis in the Trent Valley which has highlighted some of the issues with using EA ALS data for geoarchaeological prospection, including the presence of artefacts in the data (Challis 2006). This body of work, funded by the ALSF is focussed on the identification of geomorphological features on the scale of palaeochannels and while features of anthropological origin are noted as visible in the airborne surveys, their identification is not a primary aim of the study. Smaller scale archaeological features are considered more fully by the Nether Kellett to Pannal Pipeline report (Challis 2005b), but the representation of subtle changes in topography in ALS data such as might be representative of plough damaged remains, has only recently begun to be investigated (Hesse 2010).

Two projects which emerged from the final rounds of the ALSF scheme during 2008 have particular relevance to our understanding of the scope of remote sensing techniques in archaeological landscape investigation. The first illustrates how targeted research can begin to evaluate the potential of the full information content of ALS data. Included in this project was an assessment of the effectiveness of ALS intensity for predicting organic remains in alluvial terraces (Challis et al. 2007; Challis et al. 2008a; Challis et al. 2011a; Challis et al. 2011b). The second involved a comparison of two digital spectral sensors and was discussed in more detail in section 2.3.2 (Challis et al. 2009).

The aims of the ALS project undertaken by Challis et al. (2009) were to investigate the use of terrestrial laser scanning to investigate soil properties and to undertake a systematic investigation of the backscattered laser intensity component of ALS data, which had been tentatively noted in previous studies to be negatively correlated to ground moisture levels (Challis 2004; Challis 2005a). Although the use of terrestrial laser scanning was unsuccessful, the second stage of the project was more fruitful, with features identified from airborne ALS intensity data. The work undertaken also identified the value of earth resistance survey as a proxy for ALS intensity data and as a useful tool for ground truthing the aerial survey results (Challis et al. 2011b). This adds to the unpublished work undertaken in 2005 which perhaps

indicated a strong correlation between ground penetrating radar (GPR) survey and ALS intensity (Challis 2005b). The report concluded that although there was a significant non-linear relationship between soil moisture content and ALS intensity values, the equi-finality resulting from the complicated combination of the variables affecting the study prevented any form of predictive modelling from the data sampled (Challis et al. 2011b:308).

The ALS data collection technique was shown to affect intensity significantly between swaths from individual flight-lines of data acquisition. To correct this and prevent the masking of subtle changes in intensity (as identified by Challis et al. 2008) the intensity data was normalised to the elevation of the test site, but this was found to provide little improvement in the imagery (Challis et al. 2011b). The normalised data did provide the means with which to create difference maps that were shown to be better suited to geoarchaeological feature detection (Challis et al. 2011a:9). The work undertaken by Challis et al. concluded that while intensity data could add to visual analysis of topographic models, particularly in a geoarchaeological context and for some cropmark features (2011a:7), it was of limited usefulness as a predictor for organic deposits. However the above research was severely limited by three factors: i) the low spatial resolution of the ALS data (less than one hit per m²); ii) the extremely wet ground conditions in which the ALS was flown in July 2007, and iii) the suggestion that the differences in reflective properties of the features identified were not sufficient to be detected, an assertion that could not be clarified due to the lack of contemporary ground or airborne spectral data.

The use of repeated surveys and higher resolution surveys may have helped to clarify some of these issues but as the project was based on archive data this was not possible. It is also considered that following the work of Coren et al. (2005) and Höfle and Pfeifer (2007) much better methods for reducing the variance within intensity datasets have been developed than were applied during the ALSF funded research. With claimed reductions of variation to a tenth of those originally observed between flight swaths (Höfle and Pfeifer 2007:415), current research indicates that in order to be of use, ALS intensity values should be radiometrically calibrated in addition to being normalised for changes in elevation (see technical review section 2.11.4 below). Radiometric calibration would enable direct comparison between multi temporal ALS intensity data and also to spectral imagery of the same wavelength. The application of better correction techniques along with radiometric calibration could pave the way to a better understanding of the intensity component of the ALS data and ultimately to improved archaeological feature detection.

ALSF funded projects incorporating ALS or other remote sensing data have made an important contribution to advancing the use of such techniques for archaeological prospection since 2004, however it is worth noting their limitations for advancing academic use of ALS data for

archaeological research. Firstly, they make up only a very small body of work even within the ALSF scheme and their results, while highly significant, have been slow to filter through to a more mainstream professional and academic audience, despite internet publication. Secondly, the work is geographically limited to English landscapes under threat of aggregate extraction leading to the predominance of alluvial areas as project sites. Finally, the limits of the funding rarely stretch to acquisition of new data thus forcing a reliance on archived data of variable source and original purpose and consequently the unsuitability of these data has sometimes led to the curtailing of project aims.

2.4.3 *Non-ALSF funded ALS Research*

Research undertaken in an academic context in the UK has focused on the use of remote sensing to augment existing landscape research projects such as the Vale of Pickering or Hayton landscape rather than on the technical development of processing techniques (Powlesland 2006; Halkon 2008). These projects differ from those discussed in the previous paragraph as they received Natural Environment Research Council (NERC) funded survey flights, rather than relying on archive EA data². However for both, poor spatial resolution (less than 1 hit per metre) was noted, a consequence of flying at the optimal height for simultaneous digital spectral data collection. These ALS data thus proved insufficient for detailed analysis of archaeological features as part of these projects and was therefore only used for basic terrain modelling and georectification of other airborne imagery (Opitz pers.comm 2009a; Powlesland pers.comm 2010).

In a global context, exploration of the full potential of ALS data for investigating the historic environment has generally been more rapid in pace and more technical in nature than in the UK. Studies in Germany and Italy have looked at the potential for full waveform ALS acquisition to improve vegetation filtering, thus enhancing archaeological feature recovery rates (Doneus and Briese 2006; Lasaponara and Masini 2009). Recent work has focussed on developing new visualisation techniques for ALS-derived DTMs; moving away from shaded relief images to develop visualisations that highlight archaeological features. Kokalj et al. (2011) provide a non-directionally biased method of illuminating DTMs with the Sky-View Factor, while Hesse's Local Relief Model procedure (2010) provides the potential for preservation and examination of microtopography, simplifying the extraction of feature height data. Although there is yet to be a formal, quantitative review of these techniques³, their recent publication reflects the increased

2 The Landscape Research Centre from which the long-term research into the Vale of Pickering has been conducted, has also undertaken ALSF-funded projects. For the purposes of disambiguation the ALS data discussed here was not acquired as part of an ALSF project.

3 Although Challis et al. (2011) have recently provided a review of suitability of some ALS visualisation techniques based on unquantified visual assessment of feature detectability.

application of ALS data as a tool for landscape archaeology and a requirement for visualisation techniques that are driven by archaeological research imperatives.

In Italy, investigations at the ruined Roman town of Aquileia have included studies of the integration of ALS intensity with satellite data for identifying cultural heritage (Coren et al. 2005) and integrating ALS data with hyperspectral data (Sterazi et al. 2008), which will be discussed in more detail in section 2.5 below. Some projects have sought to improve acquisition and processing techniques, including experimentation with different platforms, such as helicopter-based ALS survey in Ireland (Corns and Shaw 2009). There has also been some work to improve acquisition beyond the limits of the sensor parameters by improving survey strategy. This was demonstrated most effectively by the survey of Maya, Mexico where a number of consecutive ALS surveys were combined into a single, higher resolution digital terrain model (Chase et al. 2011).

Perhaps some of the most innovative work has been undertaken by Doneus et al. (2010) beginning to explore and understand the potential of the ALS point cloud with comparison to contemporary terrestrial laser scanning. This methodology although still under development, is significant as all other published archaeological research to date has used rasterised data interpolated from the ALS scan (section 2.11.3) rather than the point cloud itself.

As is typical for the adoption of a “new” technology, ALS data have become increasingly widely used for a variety of landscape archaeology projects with relatively little formal evaluation of the strengths and weaknesses of the technique. The majority of historic environment research using ALS is based on archive data and consequently results can be disappointing unless factors intrinsic to the processing of the data, such as spatial resolution, accuracy and vegetation filtering, are considered. Critically, ALS data cannot capture the full information content of a photograph in terms of vegetation and soil changes and therefore is most powerful, and most easily interpreted, when analysed alongside other forms of aerial imagery (Crutchley 2006).

2.5 Multi-Sensor Survey

2.5.1 *Complementarity*

Airborne multi-sensor survey is a natural progression of the established multi-method investigation of historic landscapes which has traditionally included aerial photographic analysis, walkover survey and field-walking sometimes leading to geophysical survey and excavation (e.g RCHAMW 2009). The main benefit of a multi-sensor approach to archaeological survey lies in the complexity and variability that is characteristic of past human interaction with the landscape. Although a useful shorthand, the term “archaeological features” does not import the complexity or variety of the changes in local environment that are identified as belonging to the historic environment. In reality these features vary hugely in topology, topography and structure and they can be apparent as direct changes to the surface of the land or as proxy changes to soil and vegetation caused by sub or near surface features. They may not be visible at all, masked by soil, vegetation or other environmental conditions. In all likelihood they will also have been altered, or be in a state of alteration, by taphonomic processes.

It is clear that no single sensor could detect such a range of characteristics. The strength of multi-sensor survey therefore is in the complementarity of the data that can be collected by deploying multiple sensors and thereby allowing different characteristics of the archaeological features to be detected. This complementarity can lead not just to improved rates of detection but to a better understanding and interpretation of the features detected and their surroundings. Prospecting for features in a landscape is a selective process; picking out by hand or through automated processes the areas in an image that have attributes that are believed to represent archaeological features. As with any decision-making process, the more information that can be gathered about these areas the better informed their interpretation can be.

2.5.2 *Barriers to Multi-Sensor Survey*

While in an ideal world airborne multi-sensor survey would be routine, the application of multiple sensors is challenging. Although recent advances in sensor technology have removed some of the barriers to simultaneous survey of airborne spectral and ALS data, the specification and application of multiple airborne datasets are not without challenges. The choice of sensor and its calibration to detect archaeological features in a given landscape is determined predominantly by the nature of the features that are anticipated, however in reality our current understanding of how best to apply the technology is limited. Many of the reasons for this stem from the use of archive airborne data that has been collected, processed and visualised for other purposes such as environmental and hydrological survey without assessment of the impact of

the decision making processes behind the final product. Additionally, there has been little quantitative study to assess the impact of different visualisation techniques on the accuracy of feature mapping and interpretation from airborne remote sensing data. Add to this the impact of geology, soils, season and rainfall and the variety of factors affecting the detectability of a feature by a particular sensor becomes very complex. Use of multiple sensors can help to pick apart some of these factors, especially so if the surveys are contemporary.

Some of the barriers to the use of multi-sensor survey for any area are clear. Firstly, data of the quality, timeframe and resolution may not be available from archive sources and is often prohibitively expensive to commission. Secondly, obtaining contemporary datasets for ground to airborne data comparison is logistically challenging yet essential for certain datasets like earth resistance where results are highly condition dependent. Thirdly, the large quantities of data produced by this type of comparative analysis are difficult to manage without specialist software and data storage capacity. Finally and crucially, in the field of archaeology the understanding of how to utilise the data from some airborne platforms is in its infancy and this is especially true of digital spectral data. This can make efficient extraction of useful information from this wealth of data extremely difficult.

For these reasons, published studies comparing airborne sensors have each tended to be limited to just two datasets; most often the comparison of lidar data with archive aerial photography (Bewley et al. 2005; Challis et al. 2008c). The correlation of digital spectral sensors has been touched upon by work in the Vale of Pickering and Trent Valley (Powlesland et al. 2006; Challis et al. 2009) but less work has been done to examine correlation between sensors of different types. Where both spectral and topographic data have been available, such as in the study of the remote sensing techniques to the Salisbury Plain Training Area (Barnes 2003), the combined analysis has focused on objectives such as ascertaining land cover categories via visual interpretation rather than the archaeological information content. Where airborne data have been compared with geophysical data the greatest challenge has been obtaining datasets that are contemporary to ensure comparability (Challis et al. 2011b) Consequently gaps in our understanding remain, specifically surrounding the complementarity of digital spectral data and ALS data and correlations between airborne sensors of all types and ground based geophysical techniques.

The only study to date to explore fully the complementarity of CASI, ATM and ALS survey, was undertaken in Crete (Rowlands and Sarris 2007). Here the focus of the project was on an area typified by exposed soil and little vegetation cover, with upstanding archaeological remains in addition to known subsurface features identified through geophysical survey (Rowlands and Sarris 2007). Automated classification of pixels was used to define archaeological features in

the multispectral data, and was successful in defining upstanding stone remains from the surrounding bare earth and also appeared to correlate with some features known from geophysical survey (Rowlands and Sarris 2007:798). The project was hampered by the spatial resolution of the airborne data (2m or greater) leading to mixed pixels in the classification, but provides a potential model for processing and interpreting multiple airborne datasets that could be applied to archaeological sites elsewhere. However, to apply the method used for the Cretan site to a UK site directly would require significant altering of the techniques used to take account for the presence of vegetation and the fact that the majority of upstanding features would not be stone built.

2.5.3 Digital Data Fusion

While digital fusion techniques in airborne remote sensing archaeology are in their infancy, the select number of instances where they have been applied have shown great potential. Experimentation with data fusion has formed a key part of the investigation of the ruined Roman town of Aquileia in north-west Italy (Sterazi et al. 2008; Traviglia and Cottica 2011). In this project ALS and hyperspectral data were combined using what they term low (e.g. GIS overlay) and high (e.g. digital combination) level processing, illustrating the importance of ALS topographic and intensity data for improving the classification of features in the spectral data (Sterazi et al. 2008, 371). By integrating the ALS DEM and spectral data this project was able to map spatial correlation of mineral deposits, distribution and drainage of deleterious materials on the surface and vegetation cover maps that were sensitive to terrain slope and / or elevation (ibid) though no details of how this was undertaken were given. It was also not clear whether this analysis was quantitative or simply visual, and to what level data integration improved detectability of features.

Fusion techniques have been shown to be successful in other applications, such as Kvamme's (2006) use of continuous data integration of six geophysical surveys. In this study the technique was shown to reveal the interrelationships and underlying dimensionality of the data collated through the generation of new quantitative information (Kvamme 2006:268). Techniques such as these remain to be fully explored in digital airborne data, but need to be supported by quantitative methods of feature detection that are both replicable and comparable across different sensors and visualisations.

2.6 Summary of Archaeological Applications

What is evident from the existing studies is that airborne digital remote sensing in archaeology is still an emerging field with relatively few studies undertaken and little clear guidance as to how the data should be acquired, processed and interrogated. ALS data have been embraced enthusiastically without general consideration of the limitations of the data processing techniques and there is a lack of published technical data to support the future use of these data. The remote datasets have been proven to be useful for mapping known archaeological features and prospecting for new ones (Bewley et al. 2005; Oxford Archaeology North 2007). However, review of the existing literature illustrates weaknesses in our understanding of how these techniques can best be applied to archaeological research. The techniques for processing remotely sensed data in the UK have seldom been made public, and those that have been published exist only as grey literature reports. This prevents users from identifying a body of tested processing techniques specifically designed to maximise the visibility of archaeological features, and also precludes thorough assessment of the accuracy of interpretations derived from the data. Currently our use of airborne remote sensing data lacks peer reviewed critique of processing methods such as those that can be found in other disciplines (e.g. Cobby et al. 2001; Lloyd et al. 2002).

It has been shown that many of the projects to date adhere strictly to a visual mapping protocol designed for aerial photography and consequently archaeologists are failing to exploit the full data content and potential of the airborne ALS and spectral data available in the UK. Due to a necessary reliance on data collected for purposes other than archaeological survey, there have been few opportunities to attempt fusion of topographic and spectral data, limiting our understanding of their complementarity. It is envisaged that application of data fusion techniques, such as those used by Kvamme (2006) to interpret multiple geophysical surveys could significantly enhance our understanding of the multidimensionality of airborne remotely sensed data. Several projects have explicitly or implicitly noted the tendency for linear features to dominate mapping from airborne sensors, with circular or amorphous features being less easily recognisable (Winterbottom and Dawson 2005:218; Rowlands and Sarris 2007:798). Techniques need to be developed to improve detection of non-linear features and those characterised by earthen structures or negative cuts rather than hard construction materials such as stone. A research strategy should be developed that tackles the issue of how airborne remote sensing techniques can best be applied to sites more characteristic of those found in the UK than those successfully surveyed in the Mediterranean region.

The value of ground observations as a support to airborne survey has also been made clear in a number of projects, however there has been no systematic analysis of the complementarity of geophysical techniques such as earth resistance survey and ground penetrating radar (GPR)⁴. This would seem a particularly important development to aid our understanding of the nature of features that have little or no topographic representation and are therefore only visible due to the proxy effects on soil colour, texture and plant growth.

Finally, remote sensing projects in the UK to date have been dominated by the study of alluvial valleys (defined as areas of fertile soil deposited by flowing water on flood plains, and therefore of prime importance for arable production). While this is understandable given the archive of remotely sensed data collected for floodplain management purposes, and has added much to our understanding of the data, it is to the detriment of other areas which could arguably benefit more from airborne remote sensing due to their inaccessibility or unsuitability for other survey techniques. To date no work has been undertaken to examine the potential for application of ALS and hyperspectral survey to investigate archaeological remains in areas of marginal or unimproved vegetation, such as upland moors, heathland or areas dominated by pastoral regimes rather than arable farming. Yet work on the sand dunes and machair environment in Scotland has illustrated great promise for the use of remote sensing in non-alluvial environments (Winterbottom and Dawson 2005). Although the risks to historic landscapes under intensive arable cultivation are severe, in the UK this land use accounts for just over a quarter of land cover (Morton et al. 2011). This review has highlighted the need to assess the impact of ARS in non-arable areas which account for the majority of land cover in the UK at present (Morton et al. 2011).

2.7 Conclusions

From examination of the current literature it is clear that while there is a growing body of research on the subject, there are a number gaps in our understanding of the application of both ALS and digital spectral data to archaeological research questions. It can be concluded that:

- a) While a number of studies have attempted to broaden the scientific understanding of the visibility of anomalies detected in ARS data, this has rarely been done in a thorough or systematic way. An approach which incorporates systematic multi-sensor survey and contemporary ground observations is required to further understanding beyond empirical observations alone.
- b) Research in the UK is almost entirely limited to one environment - alluvial valleys. To

4 Although some work in this vein is currently being undertaken under the auspices of the DART project.

improve the application of these techniques, archaeological sites situated in and typical of other environments must be incorporated into the sampling strategy.

- c) Following a generally positive initial reception, all “new” ARS technologies have proved to have limitations for archaeological research. Some of these limitations are linked to a lack of scientific understanding of the techniques and reliance on second-hand data. It is clear that these limitations are mitigated to an extent by incorporating data from complementary sensors. However the quantity of data generated requires the development of new, streamlined ways of integrating the surveys without losing archaeological information.

Technical Literature Review

2.8 Introduction

The following section gives the detail of each of the principle technologies underlying the current research, from the concept of archaeological feature detection in aerial imagery (section 2.7) to the technical background of the airborne remote sensing techniques. The review sections covering digital spectral imagery (section 2.10) and airborne laser scanning (2.11), also comprise the details of processing techniques that may be applicable to the detection of archaeological features (Objective 6). Geophysical survey background and techniques are also given in section 2.12 with respect to their implementation as ancillary data for the ARS analysis as part of this project.

2.9 Archaeological Feature Detection in Aerial Imagery

Aerial prospection for archaeological features has been practised for almost a century and relies on the detection of topographic, soil or vegetation changes caused by surface or sub-surface features. With 100 years of expertise in using aerial photographs for archaeological purposes and the establishment of English Heritage's National Mapping Programme in 1988, aerial photography is one of the most widely used, and best understood, methods of prospection and recording of archaeological sites (Horne 2011).

The most elusive form of proxy feature that can be detected from the air is the vegetation or crop mark. In principal these are categorised into two groups - positive and negative (Wilson 2000). Positive marks occur when the underlying archaeological feature promotes growth and health in the vegetation causing it to appear greener and taller than the surrounding vegetation. Conversely negative marks occur when the underlying archaeological feature inhibits growth, causing stunting and early failure in times of stress (figure 2.1). The changes thus caused have to be sufficiently different from the surrounding soil and vegetation in terms of their physical properties that they can be detected (Beck 2007).

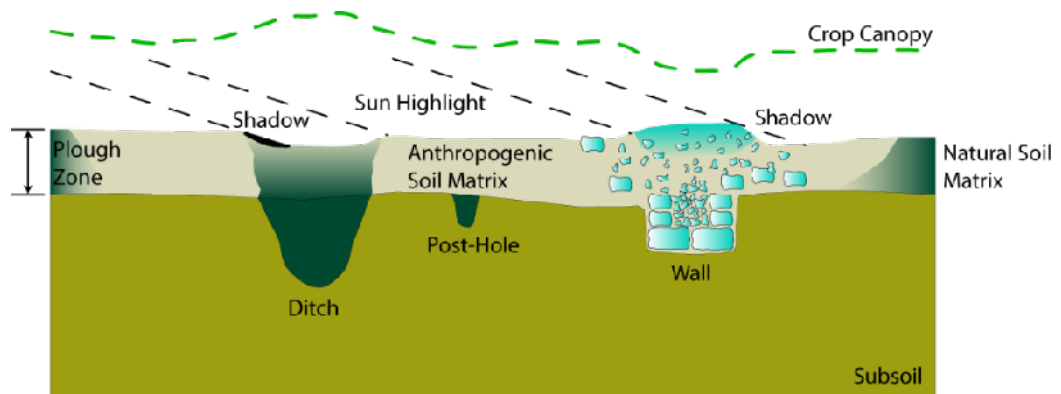


Figure 2.1: Schematic of how surface and subsurface archaeological features affect plant growth (after Beck 2009, AARG Teaching Resource)

Although the general principles of crop mark visibility in terms of soil moisture deficit are well understood (Penman 1948; Smith 1967; Evans and Jones 1977; Riley 1980, Hejzman and Smrz 2010), the visibility of these proxy marks is heavily dependent on a large number of factors including geology, season, and vegetation type and their appearance is still difficult to predict or model. In addition, most aerial imagery is captured in monochromatic or the visible spectrum which may inhibit the recording of nascent marks.

2.10 Digital Spectral Imaging

This section introduces the theory behind digital spectral imaging commonly referred to as multispectral or hyperspectral imaging.

2.10.1 General Theory

The light that can be detected by the human eye forms only a small section of the spectrum of electromagnetic energy emitted from the sun and other sources as shown in figure 2.2. The spectrum is generally divided into wavebands of different wavelengths.

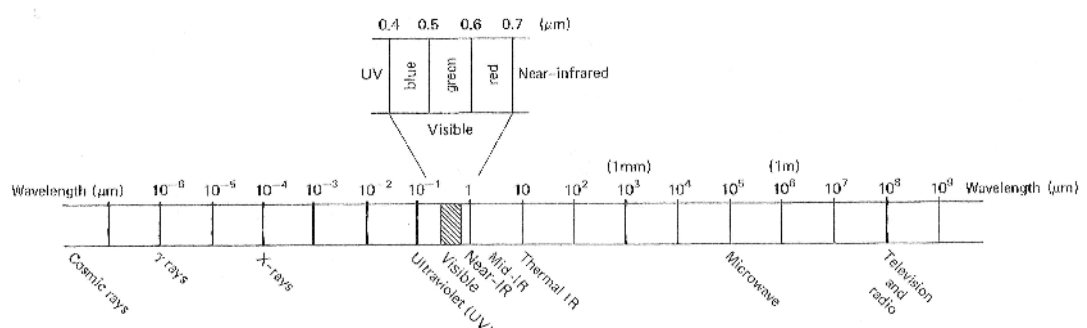


Figure 2.2: Electromagnetic spectrum reproduced from Lillesand et al 2009:5)

All materials absorb or reflect light of different wavelengths depending on their physical, physiological or chemical properties. Using a passive sensor, reflected light can be measured and recorded from an airborne platform. Table 2.1 details the four most common airborne spectral sensors in the UK.

Name	Type	Specification	Spectral Range	Typical Ground Resolution
Airborne Thematic Mapper (ATM)	Multispectral (VNIR, SWIR and Thermal)	12 bands specified to coincide with Landsat TM channels	420-1300nm	3-5m
Compact Airborne Spectrographic Imager (CASI, CASI-2, CASI-3)	Multispectral (VNIR)	512 pixels across swath, up to 18 spectral bands	405 - 950 nm	1-3m
Eagle	Hyperspectral (VNIR)	1000 pixel swath width, 2.9nm bandwidth	400 - 970nm	1-3m
Hawk	Hyperspectral (SWIR)	320 spatial pixels, 244 spectral pixels 8nm bandwidth	970 - 2450nm	2-6m

Table 2.1: Basic specification of the most common airborne spectral sensors

All spectral data must be geo-corrected using data collected from the plane's Global Positioning System (GPS) and Internal Measurement Unit (IMU). In theory this can be undertaken without ground control measurements, however results are often poor resulting in large spatial errors. The spectral data is most useful when further correction is performed using a high accuracy DEM and ground control points. For this purpose, spectral sensors are now frequently flown in tandem with ALS systems.

2.10.2 Plant Reflectance

Vegetation reflects energy from the non-visible portion of the spectrum. The biological understanding of plant reflectance across the electromagnetic spectrum is an area that has been largely ignored by archaeological remote sensing specialists with the exception of Verhoeven's work on NIR photography (Verhoeven 2009). The principles are worth repeating here with reference to the use of non-visible wavelengths to detect changes in vegetation that may be caused by underlying features.

Healthy vegetation absorbs as much as 70-90% of incident radiation, mostly in the blue and red wavelengths, centred on 450nm and 670nm respectively (Rabideau et al. 1946; Knipling 1970; Woolley 1971). The absorption and reflectance is a consequence of the cellular structure of the

leaf as shown in figure 2.3. Wavelengths in the NIR region however are scattered by the cell interfaces in the mesophyll tissue, causing light of these wavelengths to be reflected and transmitted through the leaves (Gates 1970; Knipling 1970; Slaton et al. 2001). In healthy leaves 40-60% of the NIR light is reflected (Gates 1970) although the transfer of these figures to canopy level is complicated by additive reflectance in areas of dense canopy and a range of other effects such as incidence angle, leaf orientation, shadow and soil background reflectance (Colwell 1974). An example of a healthy vegetation curve is given in figure 2.4.

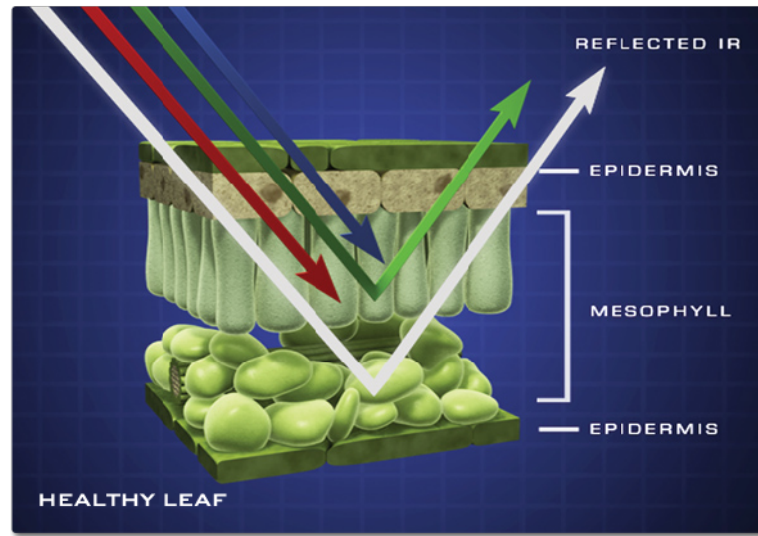


Figure 2.3: Schematic of Light reflectance from a leaf structure (credit Jeff Carns: http://missionscience.nasa.gov/ems/08_nearinfraredwaves.html)

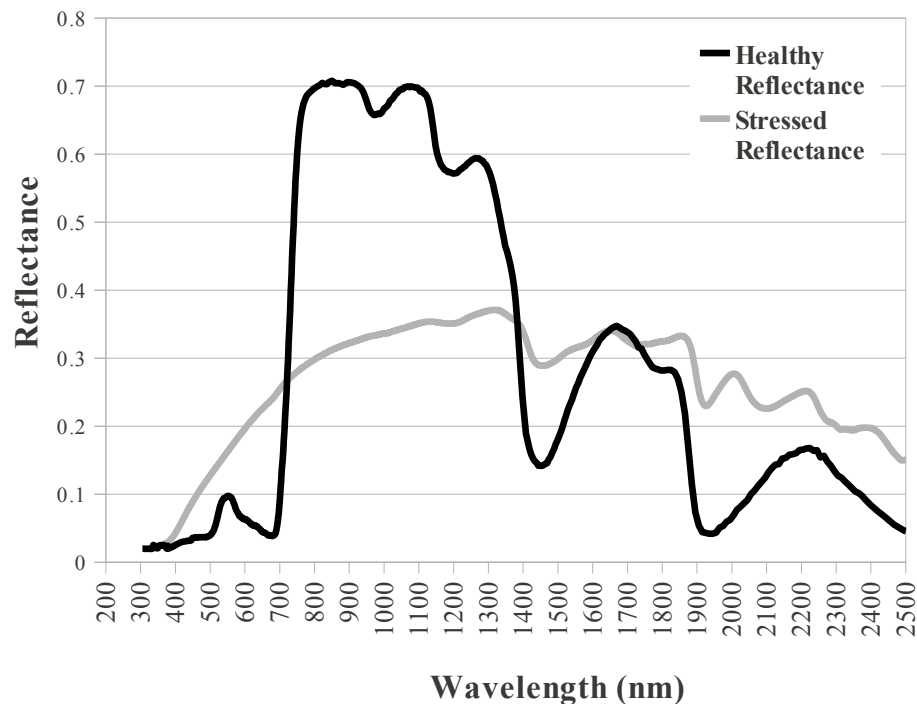


Figure 2.4: The spectral response of healthy and stressed vegetation (data courtesy of USGS spectral library)

Senescent or stressed vegetation exhibits different spectral properties, due to the rapid decay of the chlorophyll pigment and loss of absorption properties (Carter and Knapp 2001). These changes can be detected in the visible region as a yellowing of the leaf matter known as chlorosis (Hendry et al. 1987). In the NIR, reflectance is not related to pigmentation but can be affected by changes to the internal structure caused by biotic agents such as fungi or abiotic agents such as drought (Jackson 1986; Slaton et al. 2001). The NIR region has been used as a pre-visual indicator of stress due to the fact that changes in reflectance of these wavelengths happen gradually, rather than the abrupt “wilting” event in the visible region (Carter and Estep 2002). There is some debate over exactly how visible the signs of early stress are in this region particularly when using 4 band aerial photography (Verhoeven 2009:199), but stress, particularly drought, causes a significant drop in NIR reflectance as shown in figure 2.4. This allows the NIR region to be used as an indicator of the state of vegetation vigour, making it easier to detect changes in this region than in the visible wavelengths.

2.10.3 Vegetation Analysis

Vegetation indices are numerous in environmental remote sensing literature and are based on the premise that algebraic combination of spectral bands can highlight useful attributes of vegetation health and growth better than the study of either individual bands or true / false colour RGB images (Ray 1994). Over 150 of these indices have been published in remote sensing literature but as discussed in the review of relevant literature above (section 2.3.2), these have rarely been tested systematically as tools to highlight vegetation changes caused by archaeological features. A notable exception to this is the work of Traviglia (2006), which compared a simple red / NIR ratio, the Normalised Difference Vegetation Index (NDVI) and Modified Soil-Adjusted Vegetation Index (MSAVIS2) for 3m resolution hyperspectral imagery. The most commonly applied index for archaeological analysis is the NDVI (Winterbottom and Dawson 2005; Traviglia 2008; Challis et al. 2009) although rarely is any justification given for the selection of this index over any other. Testing a range of indices would give a measure of their individual usefulness but also of their relative value to each other for the landscape and land cover in the study areas.

The indices used for any archaeological study need to be selected carefully so that they have a substantial biophysical (as opposed to purely numerical) basis. This is crucial to the aim of understanding the physical and biological parameters that influence the representation of archaeological features in the data. The underlying theory is that vegetation indices will aid the identification of contrasts in plant quality, vigour and stress, all of which could be related to the presence of upstanding or buried archaeological features (section 2.9).

As so little work has been done in establishing the use of vegetation indices for prospection of archaeological features, guidance as to which of the many indices available was taken from the selection of indices made by Dr. Gregory P. Asner of the Carnegie Institution of Washington, Department of Global Ecology, on behalf of ENVI (ITT Visual Information Solutions 2010). The indices that are potentially appropriate to identifying vegetation stress caused by archaeological features can be grouped into five categories as detailed below. All indices are referred to by their acronyms in the text with full reference in table 2.2.

Broadband Greenness

The broadband greenness indices are the simplest measures of the overall amount and quantity of photosynthetic material in vegetation, and are sensitive to chlorophyll concentration, canopy leaf area and architecture (Asner 2008). Indices such as the NDVI (Rouse et al. 1973), compare reflectance measurements from the peak of reflectance in the NIR to a measurement taken in the red range, allowing the amount of green vegetation to be estimated (Asner 2008). They allow for basic assessment of the health and vigour of vegetation for any purpose. In addition, the broad band width makes these indices suitable for a wide range of multispectral and satellite sensor applications, thus they are very commonly used in environmental applications.

Four broadband indices were identified as being suitable for the aims of the current research, the NDVI, SRI, EVI and ARVI. Of these the NDVI is among the oldest and most well used indices and is one of the few indices to be applied to archaeological investigations (Traviglia 2006).

Although robust in a wide range of conditions it saturates in areas of dense vegetation. The SRI ratio of the highest reflectance and highest absorption bands is also well established and understood and effective over a wide range of conditions, but like the NDVI has a tendency to saturate in areas of high Leaf Area Index (LAI) (Tucker 1979). The EVI was designed to correct the NDVI for soil signals and reduce the impact of atmospheric effects, making it more useful in dense vegetation conditions where the NDVI and SRI may saturate (Heute et al. 1997).

Likewise, the ARVI is an enhancement to the NDVI that provides correction for atmospheric factors, particularly aerosols, by using reflectance in the blue band to correct the red reflectance (Kaufman and Tanre 1996).

Narrowband Greenness

Indices that fall into the narrowband greenness category work on the same principle as those in the broadband greenness category, by comparing the NIR and red portions of the spectrum. They provide a more sophisticated measurement of vegetation quality by sampling the red edge portion of the spectra, which refers to the region of rapid change in reflectance of chlorophyll between 690nm and 740nm (Asner 2008). Unlike the broadband category, these indices require

high spectral resolution data to allow them to be more sensitive to changes in vegetation health and thus more suited to airborne spectral sensors.

The first of the narrowband indices RENDVI and MRESRI are modifications of the NDVI and SRI indices respectively, using bands along the red edge rather than reflectance peaks to identify vegetation stress. In addition, MRESRI incorporates a correction for leaf specular reflection (Gitelson et al. 1994; Datt 1999; Sims et al. 2002). MRENDVI is a modification of the RENDVI to incorporate a correction for leaf specular reflection. The REPI is a measurement that is more sensitive to changes in chlorophyll concentration, with greater chlorophyll concentration moving the red edge to longer wavelengths (ibid). This index uses the red edge position, defined as the wavelength of the steepest slope within the range 690nm to 740nm (Curran et al. 1995).

Light Use Efficiency

These indices are used as indicators of how efficiently vegetation is able to use incident light for photosynthesis and are a proxy for vegetation growth rates (Asner 2008). The most appropriate index in this category was the SIPI, which can be used to detect physiological stress and has a decreased sensitivity to canopy structure (Penuelas et al. 1995).

Dry or Senescent Carbon

Indices that give a measure of dry or senescent carbon such as PSRI (Merzlyak et al. 1999), are primarily used to identify vegetation that is dead or dormant via increases in the amount of carbon in lignin and cellulose (Asner 2008).

Leaf Pigments

This category of vegetation indices are designed to provide a measure of the levels of stress related pigments including carotenoids and anthocyanins and do not measure chlorophyll (Asner 2008). The presence of these pigments can indicate plant stress before it is observable to the human eye and can be calculated using ARI1 and ARI2, (Gitelson et al. 2001).

Tasseled Cap Transformation

In addition to band ratios and indices, digital spectral data can be transformed mathematically in a variety of ways to determine environmental characteristics. The most common method is the tasseled cap transformation developed by Kauth and Thomas (1976). A tasseled cap transformation rotates the spectral data in such a way that the new bands have defined meaning for vegetation analysis.

The first tasseled-cap band corresponds to the overall brightness of the image and is a weighted

Index	Abbreviation	Formula	Category	Description
Normalized Difference Vegetation Index	NDVI	$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}$	Broadband greenness	Normalised difference of green leaf scattering in near-infrared and chlorophyll absorption in RED.
Simple Ratio Index	SRI	$SR = \frac{\rho_{NIR}}{\rho_{RED}}$	Broadband greenness	Ratio of green leaf scattering in near-infrared and chlorophyll absorption in RED.
Enhanced Vegetation Index	EVI	$EVI = 2.5 \left(\frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + 6\rho_{RED} - 7.5\rho_{BLUE} + 1} \right)$	Broadband greenness	An enhancement on the NDVI to better account for soil background and atmospheric aerosol effects.
Atmospherically Resistant Vegetation Index	ARVI	$ARVI = \frac{\rho_{NIR} - (2\rho_{RED} - \rho_{BLUE})}{\rho_{NIR} + (2\rho_{RED} - \rho_{BLUE})}$	Broadband greenness	An enhancement of the NDVI to better account for atmospheric scattering.
Red Edge Normalized Difference Vegetation Index	RENDVI	$NDVI_{705} = \frac{\rho_{750} - \rho_{705}}{\rho_{750} + \rho_{705}}$	Narrowband greenness	A modification of the NDVI using reflectance measurements along the red edge.
Modified Red Edge Simple Ratio Index	MRESRI	$mSR_{705} = \frac{\rho_{750} - \rho_{445}}{\rho_{705} - \rho_{445}}$	Narrowband greenness	A ratio of reflectance along the red edge with blue reflection correction.
Modified Red Edge Normalized Difference Vegetation Index	MRENDVI	$mNDVI_{705} = \frac{\rho_{750} - \rho_{705}}{\rho_{750} + \rho_{705} - 2\rho_{445}}$	Narrowband greenness	A modification of the Red Edge NDVI using blue to compensate for scattered light.
Red Edge Position Index	REPI	$REP = 700 + 40 \left[\frac{R_{red\ edge} - R_{700}}{R_{740} - R_{700}} \right]$	Narrowband greenness	The location of the maximum derivative in near-infrared transition, which is sensitive to chlorophyll concentration.
Structure Insensitive Pigment Index	SIPI	$SIPI = \frac{\rho_{800} - \rho_{445}}{\rho_{800} - \rho_{680}}$	Light use efficiency	The Structure Insensitive Pigment Index (SIPI) is a reflectance measurement designed to maximise the sensitivity of the index to the ratio of bulk carotenoids (for example, alpha-carotene and beta-carotene) to chlorophyll while decreasing sensitivity to variation in canopy structure (for example, leaf area index)
Plant Senescence Reflectance Index	PSRI	$PSRI = \frac{\rho_{680} - \rho_{500}}{\rho_{750}}$	Dry or Senescent Carbon	The Plant Senescence Reflectance Index (PSRI) is designed to maximise the sensitivity of the index to the ratio of bulk carotenoids (for example, alpha-carotene and beta-carotene) to chlorophyll.
Anthocyanin Reflectance Index 1	ARI1	$ARI1 = \left(\frac{1}{\rho_{550}} \right) - \left(\frac{1}{\rho_{700}} \right)$	leaf pigments	Changes in green absorption relative to red indicate leaf anthocyanins.
Anthocyanin Reflectance Index 2	ARI2	$ARI2 = \rho_{800} \left[\left(\frac{1}{\rho_{550}} \right) - \left(\frac{1}{\rho_{700}} \right) \right]$	leaf pigments	A variant of the ARI1, which is sensitive to changes in green absorption relative to red, indicating leaf anthocyanins.

Table 2.2: Vegetation Indices

sum of all bands. The second tasseled-cap band is approximately orthogonal to the first and reflects the contrast between NIR and visible bands (Lillesand et al. 2008). This corresponds to greenness or the amount of vegetation in an image. Together these bands typically express 95% of the total variability in an image (Crist and Kauth 1986). The third tasseled-cap band is interpreted as an index of wetness, relating to canopy or soil moisture.

The transformation was originally undertaken on Landsat MSS data (hence the three band interpretation) but can be performed with more spectral bands, though the subsequent bands are more complicated to interpret and may not be as useful for vegetation analysis. Crist and Ciccone's (1984) extension of the concept to the six Landsat TM bands concluded that the six transformed bands occupied three dimensions categorised as soils, vegetation and a transition zone between them.

2.10.4 Soil Analysis

In the past decade there have been significant advances in the use of digital spectral data for mapping soil properties. This has been driven by the need for more accurate and spatially coherent mapping and contemporary improvement in sensors (Summers 2009:3). Although the soil matrix itself and the imaging of soil from the air are both complex areas of research, (Ben-Dor et al. 2009:39), various studies have shown the value of the visible, NIR and SWIR regions for both qualitative and quantitative recognition of soils (e.g. Ben-Dor 2002; Viscarra Rossel et al. 2006). Since the 1970s, point spectroscopy has been used in laboratory settings to analyse soils, providing the basis for research into spectral imagery. A number of research themes have developed including the assessment of salinity, erosion and deposition, contamination, moisture and organic matter. An excellent overview of research to date is provided by Ben-Dor et al. (2009).

The use of spectral data for soil analysis is far from straight forward. In terms of depth of deposit, only the A horizon (characterised as the upper mineral surface) can be imaged from the air, and detailed analysis requires high spectral resolution data to do so (Ben-Dor et al. 2009:39). Atmospheric attenuation is a major problem when analysing data for soil, particularly using data with high spectral resolution that will cover the absorption features of atmospheric gases. Therefore good quality data is a pre-requisite of this type of analysis as the changes in soil spectra can be smaller than the signal to noise ratio of the sensor (Ben-Dor et al. 2009:40). In addition to atmospheric effects, analysis has to take account of factors such as varying particle size and Bi-Directional Reflectance Distribution (BDRF) which has led to the development of specialised software (Viscarra Rossel 2008). Even with good data and appropriate processing, soil reflectance is still affected by partial coverage by vegetation, rock

outcrops, leaf litter or other deposits, all factors that will affect the outcome and accuracy of soil analysis using spectral data.

To date, the only research that has been undertaken with respect to the analysis of soil for archaeological site prospection in the UK from airborne spectral imagery is in the machair environment of Coll / Tiree in Scotland (Winterbottom and Dawson 2005) and the work of PhD researcher Kay McManus (McManus 2003). In both cases thermal inertia was calculated as a proxy for archaeological features (as demonstrated by Bellerby et al. (1990)), with unsatisfactory results due to the quality of the ATM imagery. An emerging body of work is being undertaken in Southern Europe and the Fertile Crescent where soil / vegetation fractions are much greater allowing for direct observation of the soil (Ben-Dor et al. 2001; Traviglia 2005; Rowlands and Sarris 2007). Of particular note are the results of the application of Soil Line Index by Traviglia (Traviglia 2005) for identifying changes in soil matrix. Rowlands and Sarris (2007:798) report good spectral definition of the sandstone that comprised the surface remains of the Roman basilica from the surrounding vegetation / soil. However sub-surface remains (as identified from geophysical survey) could not be linked statistically to the observed differences in visible and NIR reflectance (ibid). Although based on satellite imagery, work by Alexakis et al. (2009) show the application of spectral signatures (predominantly soil signatures) for the identification of Neolithic Tell settlements, although similar research in Syria concluded that there was no identifiable spectral signatures for Tell settlements in that landscape (Beck 2007).

Of the wider research themes cited by Ben-Dor et al. (2009), the most important from an archaeological perspective are soil moisture and organic content. Soil moisture is one of the most significant factors affecting spectral measurements (Bowers and Hanks 1965). Using the water absorption feature at 2.8 μ m, it has been shown that moisture content can be estimated using a Gaussian model (Whiting et al. 2004) and by application of the Normalized Soil Moisture Index (NSMI) for areas with low vegetation cover (NDVI < 0.3) (Haubrock et al. 2008). Although the effect of mineral and organic components still impedes modelling of water content in soils, methods are improving and as a key factor in the composition of the soil matrix consideration should be given to the impact of soil moisture when analysing other spectral properties (Ben-Dor et al. 2009:52). Thus far, no direct modelling of moisture content in relation to archaeological features has been undertaken.

Like soil moisture levels, organic content can be difficult to determine. Work by Stevens et al. (2006) has shown that Soil Organic Carbon (SOC) can be assessed from airborne imagery on a landscape scale using various indices (Bartholomeus et al. 2008). Results were very promising even in areas of low SOC and by combining the NIR and SWIR regions, Bartholomeus et al

(2008) were able to map SOC on a pixel by pixel basis. It remains to be tested whether these approaches could be used to identify varying organic content represented in archaeological features such as pits and ditches.

2.10.5 Visualisation Techniques

A number of visualisation techniques have been developed to improve digital spectral data for analysis by reducing redundancy or improving resolution. The two most common techniques for these purposes are presented below.

Principle Components Analysis (PCA)

As the spectral resolution of airborne sensors increases so too does the issue of data duplication between the wavelengths. As there is extensive between-band correlation in digital spectral data, images produced from different bands often appear to convey the same information. To reduce processing time and extract the maximum information of value from the data several transformations have been applied, the most common of which is the principle components analysis or PCA.

PCA works by concentrating the image data into fewer channels, transforming the original spectral data into a new spectral co-ordinate system of eigenvalues (Neteler and Mitasova 2008:304). In general, the first principal component image will contain the maximum variance, with the second containing the maximum not shown in the first principle component image (ibid). The number of bands created is the same as the original number of input bands, with the final band representing uncorrelated noise. While PCA is in theory the optimal linear scheme for compressing data with high dimensionality (Shlens 2009), PCA assumes statistical importance of the mean and covariance within the data. While this is a robust way of reducing dimensionality there is no certainty that the directions of maximum variance as displayed in the transformed bands will be good for the display of a given set of criteria, such as archaeological features (ibid). PCA transformation also assumes that the key information within the images is that of high variance, with low variance corresponding to noise (ibid).

There are few published examples of PCA for archaeological analysis of spectral data. The first was undertaken by Winterbottom and Dawson(2005) in their study of machair environments in Scotland. This study compressed 11 bands of spectral data into a four PC image from which a colour composite of bands 1, 2 and 4 was created and analysed (ibid). Traviglia (2006) also used the technique to analyse 102 bands of satellite spectral data for the site of Aquileia in Italy. Typically PC 1 and 2 together accounted for 98.9% of all variability in the images, with 1% being found in PC 3 and 0.4% in PC 4 and higher (ibid). However Traviglia (2006) found that

higher components did contain useful information, requiring visual assessment of all PC images. As with the former example, the PC images were viewed as RGB colour composites, but the number of contributing bands was raised to four or six rather than the standard three, though it is not stated how this was achieved. For this study it was found that grouping the spectral bands into subsets based on their intrinsic dimensionality before computing the PCA gave improved results (termed as SPCA by Traviglia 2006:129).

Pan-sharpening

Transformation techniques, such as pan sharpening, are well established in satellite remote sensing studies to improve the resolution of spectral data (Pohl and Van Genderen 1998). Although there are many pan-sharpening methods (Pohl and Van Genderen (1998) list over 100), at the most basic level these techniques all provide a way of integrating lower resolution spectral images with high resolution panchromatic imagery to produce a higher resolution spectral image.

Given the higher resolution of ALS elevation and intensity data, it is suggested in this thesis that this could be used as a substitute for the panchromatic band in a pan-sharpening technique such as Brovey sharpening, to provide a single image that combines elevation and spectral information content. No archaeological examples of this adaptation of the techniques have been found.

2.11 Airborne Laser Scanning (ALS)

2.11.1 General Theory

ALS is an active remote sensing method based on the transmission of a laser pulse and detection of the subsequent returns of the pulse as it reflects off an object. Beraldin et al. (2010) provide an excellent technical introduction to airborne lidar systems and much of the following section is synthesised from their work.

The basic principle of the system for optically measuring 3D surfaces from the air is the measurement of the time of light transit which allows the calculation of the distance between the sensor and the reflector. As the speed of light through air (0.15m per nanosecond) is known the distance can be easily calculated. The airborne sensor itself comprises the laser and projection mechanism, a GPS system and an Internal Measurement Unit (IMU) along with a system control that also records the data. The GPS provides location data throughout the survey, while the IMU records the pitch, yaw and roll of the aircraft during survey. Together these measurements are used to process the ALS data to enable correction for the movement of the

aircraft during survey and alignment to real-world co-ordinates. Although airborne systems were known to be able to record height to less than 1m accuracy in the 1970s, it was advancements in GPS and IMU technology that enabled the sensor to be used for topographic mapping (Beraldin et al. 2010:20).

While the principal behind laser scanning is simple, in practise there are a number of other factors that need to be accounted for when calculating the range. The first is propagation of the laser beam as it passes through the lens. This causes divergence of the beam that affects the spatial resolution of the sensor, (regardless of the sample density) and causes it to vary dependent on the altitude of the aircraft thereby determining footprint size.

The shape and reflectivity of the materials surveyed are also factors that affect the characteristics of the ALS data. The assumption underlying the principle of active optical measurement systems such as ALS is that the surface is an opaque, Lambertian reflector (Beraldin et al. 2010:15). However as this is never the case both the shape and reflectivity of the surface material impacts on the nature of the return waveform. Additionally a return echo from a low reflecting target such as rubber, will have a lower amplitude than that from a high reflector such as white painted road markings. This results in the higher amplitude echoes apparently floating above the surface. This type of systematic bias is typically corrected in pre-processing.

When reflected from vegetation the sensor can record multiple returns from the same beam as shown in figure 2.5. Generally four to six echoes are recorded enabling filtering of vegetation from the surface model. The detection method for triggering the recording of these echoes is explained in detail by Beraldin et al. (2010:5) with constant fraction detection being identified as the preferred method. However in pulse systems the method of echo detection is intrinsic to the sensor, not user defined. Recent developments in sensor technology has enabled the full waveform of the returned pulse to be recorded, rather than specified points in the signal. In complex environments such as woodland it has been found that analysis of the shape of the waveform significantly aids feature interpretation in the terrain model (Doneus and Briese 2006).

A number of components of the ALS system contribute to the overall accuracy of the elevation data, with the principal factors being calibration of the sensor / GPS / IMU assembly, limited accuracy of the flight path, the complexity of the target (including slope), multipath reflections and errors arising from coordinate transformation and geoid correction (Beraldin et al. 2010:30). Many of these issues can be minimised with good flight planning and systematic registration and calibration procedures (Lichti and Skaloud 2010) resulting in standard accuracies of 0.05-0.25m vertical error and 0.2-1.0m positional error.

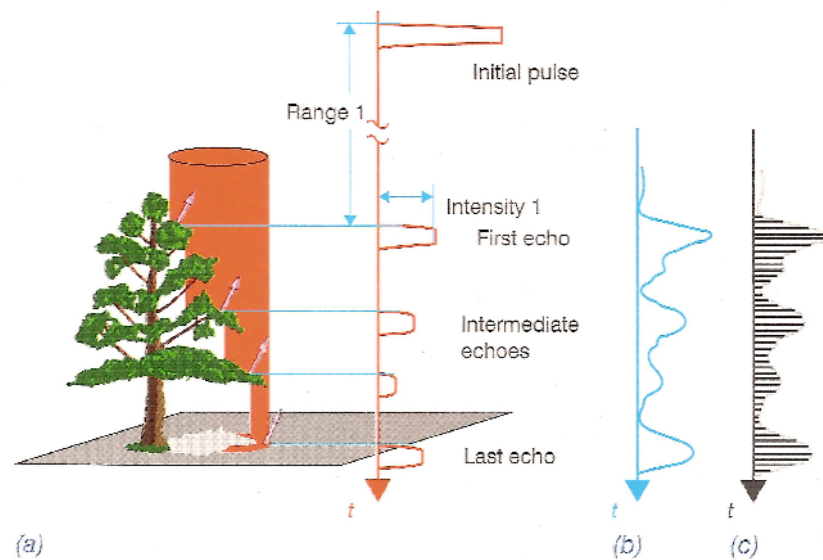


Figure 2.5: Schematic of multiple returns of Airborne Laser Scanning data, where (a) represents discrete pulse (b) represents waveform and (c) represents full-waveform (reproduced from Beraldin et al. 2010:29)

ALS data is generally measured by two factors: point density (average number of points per square metre) and point distance (average separation of points). As part of the processing, error images can be generated to highlight areas where the data is inconsistent, such as at the overlap of flightlines (figure 2.6). In addition, Briese (2010:161) highlights the use of empirical formulae for describing the accuracy of the model quality either based on the point density and slope or from the original data and the DTM (Kraus et al. 2006).

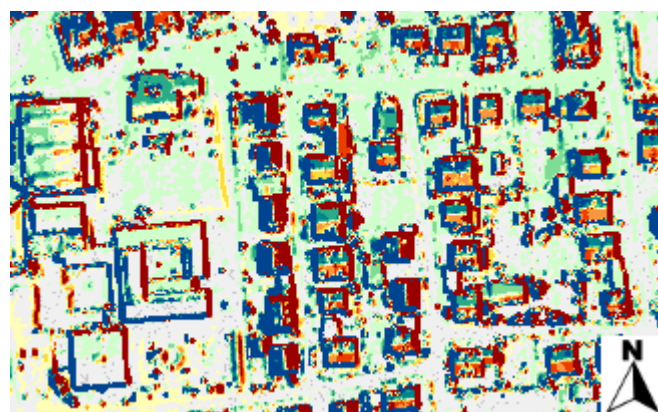


Figure 2.6: Illustration of strip height differences between flightlines with red areas indicating high error between flightline elevation values © TU OPALS, scale 1:25000

2.11.2 Filtering

ALS survey typically results in a dense point cloud of x,y,z data that can then be interpolated into a raster model. There are two different types of model: Digital Elevation Model (DEM)⁵, which gives the surface of the topography (usually recorded from the first return per pulse), including buildings, trees etc.; and Digital Terrain Model (DTM) which represents the bare earth surface stripped of vegetation, buildings and temporal objects such as cars (Briese 2010:136).

The removal of non-terrain points is undertaken by classification of the point cloud and filtering of the data, and many algorithms have been developed to automate this procedure. Sithole and Vosselman (2004) provide a detailed evaluation of many of the traditional approaches with respect to their accuracy which are generally good for rural and level terrain but fare worse in complex urban or rough, vegetated terrain. This is because the simplest approaches apply only a local minimum height filter that leads to systematic errors in hilly or rough terrain (Briese 2010:137). In addition, unsophisticated filtering techniques have been noted to remove archaeological features from the model and add artefacts (Crutchley 2010). Recently more sophisticated approaches have been developed, including the identification of breaklines such as building edges as a pre-filtering step to improve the final interpolation and segmentation based methods. Though as yet no fully automated procedure has been found that can be applied universally to all landscape areas (Briese 2010:139,150). This means that manual checking and editing of the model is necessary to improve the results of the automated process, though this tends to be far more intensive in urban areas with complex local surface characteristics (ibid).

For full waveform data, the echo width and amplitude can be used to improve the classification and filtering process particularly in areas of dense, low vegetation such as forest understory. Although these techniques are still in development they have been shown to be very effective at defining ground hits from low-level vegetation based on texture (Doneus and Briese 2006).

2.11.3 Interpolation

After filtering the point data is often interpolated into a 2.5D surface as a raster grid or vector TIN format. Any of the common interpolation methods can be used; typically inverse distance weighting (IDW), linear functions (regularised / bicubic or bilinear spline), or kriging are the most common. In practise determining the best interpolation method depends on the topology, so trialling a number of techniques on sample areas is often necessary. The accuracy of these models can then be assessed by creating an RMSE map of the difference between the input point data and output model. More sophisticated interpolations are able to incorporate

5 Digital Terrain Models are also referred to as Digital Surface Models (DSM) with the two terms used interchangeably. For consistency DEM will be the term used to refer to unfiltered ALS-derived data in this thesis.

breaklines to reduce the negative impact of smoothing when interpolating over sharp changes in topography (Briese 2010:155).

2.11.4 Intensity

In addition to the time taken, the intensity of the returned laser beam is also recorded by the ALS system. Although poorly defined by scanner manufacturers, the term “intensity” is often synonymous with the return amplitude or energy of an echo and thus is a measure of the backscattering reflectivity of the surface at the wavelength of the beam (generally between 800nm and 1550nm) (Höfle and Pfeifer 2007:415). Intensity has been used for a number of studies including environmental applications (canopy determination e.g. (Donoghue et al. 2007b), landcover classification e.g. Yoon et al. 2008) and earth science applications (volcanology e.g. Spinetti et al. 2009 and glaciology e.g. Lutz et al. 2003).

Starek et al. (2006:2) list the following factors that affect intensity values in addition to the laser power: “variations in path length, surface roughness and orientation, beam divergence, object composition, object density, saturation from background reflections, attenuation of the signal through the atmosphere, and ALS system characteristics”. While variations caused by object properties (e.g. surface roughness) are typically the focus of study, it is necessary to correct for other factors to improve image interpretation (ibid). Atmospheric effects are often left uncorrected as the short acquisition period and lack of contemporary atmospheric data for most flights makes the effect negligible (providing the goal is not to compare temporally distinct acquisitions) and correction virtually impossible. However Starek et al. (2006:4) highlight the importance of correcting the effect of variation in path length of the laser beam, (which is mostly determined by topographic change across the flight) and suggest a normalisation procedure where the intensity value is multiplied by the range of the point divided by the standard range. In a recent study by Challis et al. (2011:6) using archive data without a GPS time tag or scan angle data, this technique was adapted by using the flight height of the aircraft minus the elevation as the range measure and taking the average elevation over an area of interest for the standard range. The adapted technique was noted to give little visual improvement on the display of the intensity data but the difference map produced from subtracting the original values from the normalised ones did allow improved visualisation of the areas of maximum change (Challis et al. 2011:9). The lack of improvement seen through normalisation of the intensity data is likely to be a consequence of the low relief of the study area in this instance as the difference between minimum and maximum elevation was just 42m (ibid).

Radiometric calibration may prove to be more critical to the usability of the intensity

measurements for high level data products and particularly if they are to be compared with spectral data from other remote sensing techniques (Wagner 2010). Consequently, researchers have recently begun to develop techniques for radiometric calibration using full waveform data, which combine pre-flight laboratory calibration and the use of Lambertian targets in-flight to derive reflectance from applying radar backscatter equations (Kaasalainen et al. 2009; Wagner 2010; Briese and Lehner 2010).

2.11.5 Visualisation Techniques

Due to their subtle topography, archaeological features can be difficult to determine from the point cloud or DTM, even when the z component is scaled. To map these features some form of visualisation technique is required to highlight their presence.

Shaded Relief models

The creation of shaded relief models is the most common process used to visualise ALS data for archaeology (Crutchley 2010). This technique takes the elevation model and calculates shade from a given solar azimuth and altitude, thus highlighting topographic features (Horn 1981). Shaded relief models provide familiar, photogenic views of the landscape and can be used to mimic ideal raking light conditions favoured by aerial photographic interpreters (Wilson 2000:46).

Despite their frequent use and familiarity, shaded relief images pose some problems for the archaeological interpreter. Archaeological features that align with the direction of illumination will not be easily visible in the shaded relief model, requiring multiple angles of illumination to be calculated and inspected (Devereux et al. 2008). To mimic raking light (and so highlight micro-topography) the shaded model must also be calculated with a low solar altitude, typically 8°-15°. This means that shaded relief models work poorly in areas of substantial macro topographic change, with deep shadows obscuring micro-topography regardless of illumination direction (Hesse 2010).

Principle Components Analysis of Multiple Shaded Relief Images

As described in section 2.10.5, PCA is a multivariate statistical technique used to reduce redundancy in multi-dimensional or multi-temporal images. It has been skilfully applied by Kvamme to geophysical data (2006) and is used for minimising the number of images to be analysed due to the correlation of adjacent spectral bands. PCA has also received some attention in archaeological work (Winterbottom and Dawson 2005; Challis et al. 2008; Devereux et al. 2008).

While the PCA transformation reduces the dimensionality of the shaded relief technique, the

interpreter must still analyse a large number of shaded images to access the information content of the terrain model. Also, to ensure the most representative model of the topography, every possible angle and azimuth should be processed. At the time of writing this approach has never been undertaken; the only published method for using the technique with ALS shaded relief images used 16 angles of illumination at the same azimuth (Devereux et al. 2008). The limit on the number of input images is principally due to the relatively diminished return of new information compared with the increased costs in terms of computation and interpretation time.

PC images represent statistical variance in light levels of the shaded relief models, rather than the topographic data collected by the sensor. While this might seem an irrelevant distinction to make, the visibility of archaeological features is highly dependent on angle and azimuth of illumination. The PCA will reduce some of this directional variability but cannot account for the features that were poorly represented in the original shaded relief images. The output of the PCA will therefore be highly influenced by the selection of these factors at the outset and this could prove a limiting factor for subsequent interpretation. Consequently, the choices made in the processing of shaded relief and PC images may mask features that were present in the original ALS data. No work has been undertaken to date to establish the impact of this.

Slope and Aspect and Curvature

Slope, aspect and curvature maps are commonly used for analysing topographic data in other geographic disciplines. Slope mapping produces a raster that gives slope values for each grid cell, stated in degrees of inclination from the horizontal. Aspect mapping produces a raster that indicates the direction that slopes are facing, represented by the number of degrees north of east. Curvature mapping gives the curvature in the direction of the steepest slope and in the direction of the contour tangent. The curvature is expressed as 1/metres so a curvature of 0.05 corresponds with a radius of curvature of 20m. Convex form values are positive and concave form values are negative (GRASS Development Team 2010b)

Although common for geographical applications, there has been limited application of slope, aspect and curvature mapping for the detection of micro-topographic change relating to archaeological features, though coarse resolution aspect and slope terrain maps are well established in predictive models of site location (Kvamme and Jochim 1989; Challis et al. 2011c). It is anticipated that topographic anomalies relating to archaeological features will be identifiable in these images, in particular the slope and aspect maps may aid pattern recognition for features such as the lynchets of a field system.

Horizon View Modelling

To overcome some shortfalls of shaded relief models, specifically the issues of illumination

angle and multidimensionality of data, the technique of horizon or sky view factor has been applied recently by researchers in Slovenia (Kokalj et al. 2011). The calculation is based on the method used to compute shadows for solar irradiation models. The algorithm begins at a low azimuth angle from a single direction and computes at what point the light from that angle 'hits' the terrain. The angle is increased until it reaches the angle where it is higher than any point in the landscape (on that line of sight). This procedure is then replicated for a specified number of angles producing a number of directional files which can then be added together to produce a model that reflects the total amount of light that each pixel is exposed to as the sun angle crosses the hemisphere above it. Consequently, positive features appear brighter and negative features are darker, replicating the visual results of the shaded relief models but without bias caused by the direction of illumination.

Polynomial Texture Mapping (PTM)

Another of the techniques that has recently been trialled to improve on the shaded relief modelling is the concept of polynomial texture mapping (PTM). This photogrammetric technique uses multiple images taken from a fixed position while a light source is moved in small increments in a dome over an object to capture the reflectance of a surface and model its detail. Its applications for cultural heritage thus far have predominantly focussed on artefact recording (Earl et al. 2010), but recently there have been a number of unpublished applications of this technique to ALS data (Goskar 2010). The results are compiled into a single interactive file from which the user can vary the light source and intensity to view features in the model.

Due to the paucity of published information on this technique for landscape work, it is difficult to determine its advantages over the simpler Horizon View approach or indeed individual shaded relief images. If the model is to truly represent the interaction of light on the landscape then some element of the intensity of the return signal needs to be computed. It could be argued that the ALS intensity measurement already provides this and should therefore be factored into the model. The application of this technique is clearly in its infancy, indeed Earl et al (2010:221) make clear the case for further work on the integration of the outputs of PTM and the requirement for robust workflows to maximise the benefit of the technique.

Local Relief Modelling (LRM)

While shaded models provide useful images, there has been much recent emphasis on developing better methods for extracting the micro-topography that represents archaeological or modern features from the landscape that surrounds them while retaining the height information as recorded by the sensor. One of these methods, Local Relief Modelling or LRM devised by Hesse (2010) for analysing mountainous and forested terrain in Germany, has received

particular attention for its robust methodology and accurate results. The technique reduces the effect of the macro-topography while retaining the integrity of the micro-topography, including archaeological features by subtracting a low pass filtered model from the original DTM and extracting features outlined by the 0m contour. The advantage of this technique over the others mentioned is that it allows the creation of a model that is not only unaffected by shadow but which retains its topographic integrity allowing measurements to be calculated from it in a way that is not possible using shaded relief models, PCA or Horizon View mapping. However the extent of distortion of the micro-topographic feature extracted has yet to be quantified as the development of the model took place without any ground control data.

Although developed for mountain environments, the technique could also be applied to gently undulating landscapes to highlight archaeological features, though there are no published examples of this. Due to the isolation of the microtopography the LRM model could also have the potential to be used as a base topographic layer for digital combination with other data.

2.12 Geophysical Survey

Geophysical survey can be defined as “the examination of the Earth's physical properties using non-invasive ground survey techniques to reveal buried archaeological features, sites and landscapes” (Gaffney and Gater 2004:12). Techniques such as earth resistance survey, ground penetrating radar and magnetometry have their origins in the discipline of earth sciences but have been successfully developed by archaeologists since as early as the 1920s. They provide an alternative and complementary data source to destructive excavation techniques, increasingly allowing prospection of sub-surface features across entire landscapes (Parker Pearson et al. 2006).

The principles of the various geophysical techniques are relatively well understood and are documented in detail in a number of publications (Scollar et al. 1990; Clark 1996; Kearey et al. 2002; Gaffney and Gater 2004; English Heritage 2008). The details of each method below are synthesised from these publications and are selected with respect to highlighting the potential for complementarity with airborne survey.

2.12.1 Earth Resistance Survey

The principle of earth resistance survey lies in the differential resistance of soil dependent on its moisture content. This means that archaeological features such as the fills of ditches and buried walls can be identified from their surrounding matrix providing that there is sufficient moisture difference between the deposits to affect the resistivity when a current is passed through the ground. As water is a conductor of electricity, features with a high water content will show less resistance than features with a low water content.

The Wenner array was the earliest arrangement for passing current through the ground. However the twin-probe is far more commonly used for archaeological prospection (figure 2.7). Although less sensitive than the Wenner array, the twin-probe array gives a significant reduction in the levels of background noise, allowing archaeological features to be distinguished more clearly (Gaffney and Gater 2004:31). Due to the curving shape of the passage of the current (see figure 2.8), a 0.5m spaced twin-probe array can penetrate ~0.75m - 1m below the surface (Clark 1996:57).

Resistance is measured in Ohms (Ω) and can be converted to Ohm metres (Ωm) to allow for the expression of different volumes of material. This is particularly important when different probe arrays are used for a single survey as the Ωm units normalise the results between different survey parameters.

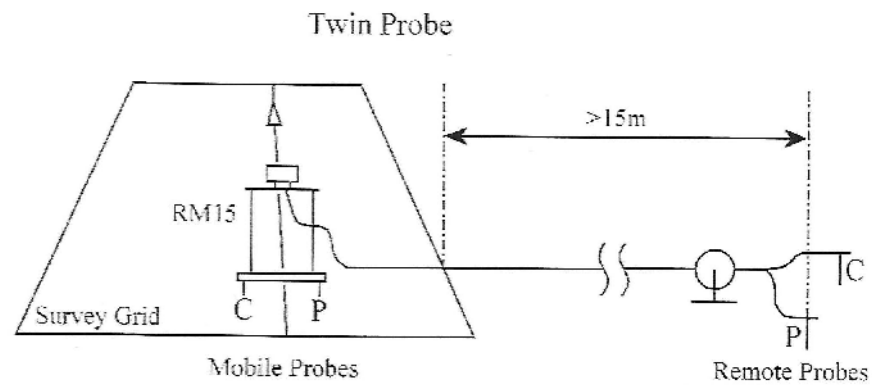


Figure 2.7: The twin probe earth resistance array (from Gaffney and Gater 2006:29)

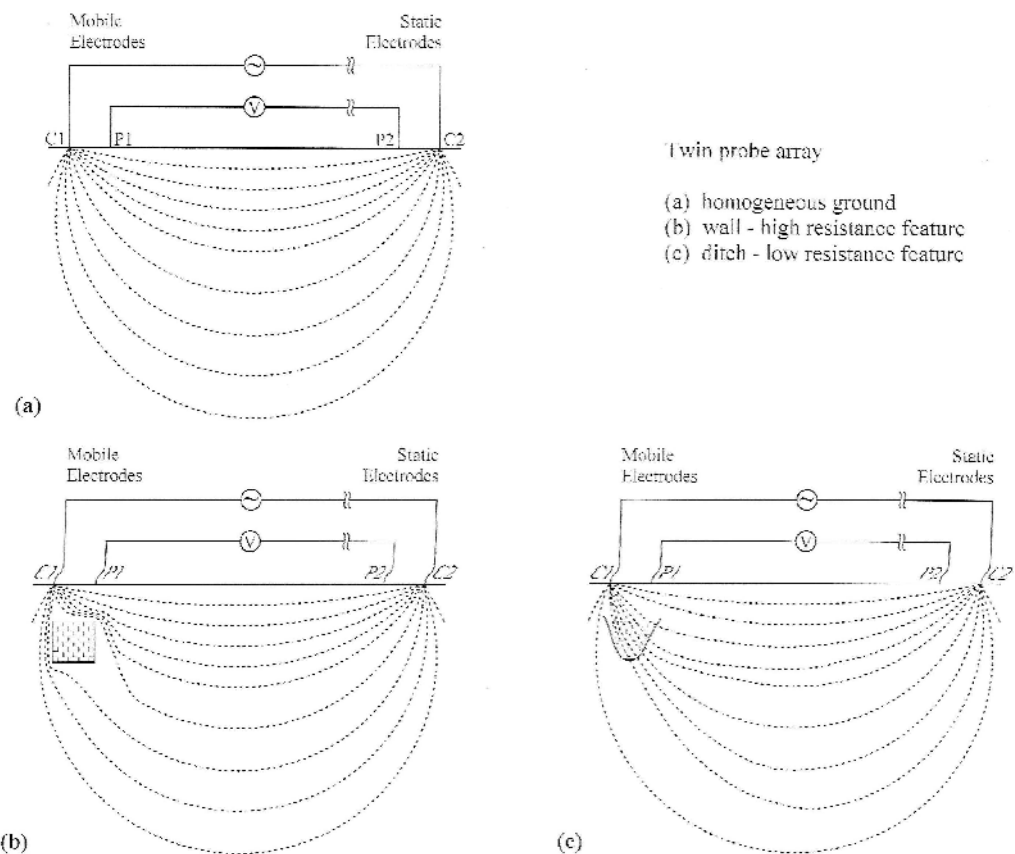


Figure 2.8: The passage of electrical current through the ground using a twin probe array from Gaffney and Gater 2006:30)

Earth resistance survey is very sensitive to local ground moisture content conditions and results vary dependant on the weather both before and during geophysical surveys (English Heritage 2008:27). This effect is particularly exacerbated over shallow, soils and quick draining geologies such as chalk (John Gale 2008 pers.comm). For this reason, earth resistance data used to should be collected simultaneously to the airborne data so that the effects of change in moisture over time can be considered negligible.

2.12.2 Ground Penetrating Radar

Ground Penetrating Radar or GPR is a term used to describe all survey using electromagnetic radiation in the range 30MHz to 12.4HHZ to record images of subsoil features (English Heritage 2008:28). Working on a principal similar to radar, an antenna is used to direct a VHF radio pulse towards the ground. When these pulses meet irregularities, part of the pulse is reflected back to the receiver unit. As with ALS survey, by measuring the time taken for the pulse to return, the distance to the feature can be estimated with more accuracy than other geophysical techniques. The high sample rate can also record the cross-section of structures with greater clarity. For archaeological survey antennae in the range 80MHz to 1GHz are used providing shallow prospection of up to 4m.

GPR survey is predominantly undertaken in transects or as area survey. With area survey repeated transects are sampled at narrow intervals and the data is post-processed to produce time-slices. GPR survey is slow compared with other techniques, meaning that its potential for landscape survey has been limited. New techniques such as those currently being trialled by the Ludwig Boltzman Institute for Archaeological Prospection, Vienna, incorporating GPR instrumentation onto quad bikes pave the way for this technique to be integrated into landscape scale geophysical survey.

The size of the GPR antenna is linked to the penetration of the pulse and also its 'footprint' which determines the minimum size of feature that can be identified. The area of this oval footprint is affected by the permittivity of the matrix and alters by depth. In typical plough soil conditions it could be expected that a 100MHz antennae would penetrate 1.5m into the soil (Conyers and Goodman 1997).

2.12.3 Magnetometry (Fluxgate Gradiometry)

Due to the ease of operation, rapid acquisition of data at high resolution and relative insensitivity to ground moisture conditions, magnetometry, or more correctly fluxgate gradiometry, is the most widely used technique in landscape scale studies. The sensor is sensitive to minute changes (in the order of 0.1 nanoTesla) in magnetic orientation caused by

two mechanisms. The first involves the heating of materials in antiquity past what is known as the Curie Point (Gaffney and Gater 2004:37). When a material is heated in this way the iron content of the material is demagnetised. As the material cools the iron is re-magnetised relative to the contemporary magnetic field of the earth in contrast to the surrounding matrix. In this way kilns, hearths and fired brick can be identified.

The second mechanism involves a change in magnetic susceptibility linked generically to human activity via two additional processes. The first is the backfilling of features cut into the substrate with topsoil which tends to be of higher magnetic susceptibility due to anthropogenic processes such as settlement and rubbish disposal (Gaffney and Gater 2004:28). The second is the action of magnetobacteria which act on minerals in the deposits and result in further enhancement of their magnetism. This mechanism allows the identification of pits and ditches whose fills are magnetically different from the surrounding substrate (ibid).

Magnetometry survey is typically only able to detect features up to 1m below the surface and is therefore not suitable for areas with deep overburden. In addition the sensors are very sensitive to background ferrous material and electrical currents.

The most commonly used sensor for this type of survey is the gradiometer, which consists of two sensors, mounted vertically. This allows the data to be corrected for background variations in magnetic field caused by geology or other sources, highlighting subtle archaeological anomalies.

2.13 Proposed Method Areas

From the technical review it is clear that there are many visualisation and data management techniques that have not been fully explored with respect to their application for archaeological feature detection. As relatively little detailed analysis has been undertaken to date, it is proposed that the current study focuses on three method areas to correlate with the archaeological imperatives that were summarised in section 2.7:

- 1) Digital Spectral Imaging – a full analysis of spectral sensitivity with regards to archaeological feature detection; the impact of data reduction techniques such as PCA and the application of vegetation indices; an assessment of land use and environmental conditions on feature detectability.
- 2) Airborne Laser Scanning - a full analysis of the impact of visualisation on feature detectability; an assessment of the value of elevation data that can be extracted for archaeological features with respect to the documentation of feature preservation; the analysis and assessment of ALS intensity as a prospection tool; an assessment of land

use and environmental conditions on feature detectability.

- 3) Data Integration – an assessment of the complementarity and relative value of multiple airborne sensors; an analysis of correlation to ground-based geophysical techniques.

2.14 Summary

This chapter has brought together the review of current literature relating to archaeological applications of airborne remote sensing and the scientific background underpinning the sensor technology (Objectives 1 and 2). The archaeological review outlined gaps in current understanding and underpins the archaeological research objectives laid out in Chapter 3 (section 2.2.1) and the case study rationale laid out in Chapter 4 (section 4.2).

The gaps in our understanding of how the ARS technologies could be applied to archaeological research questions that were identified through this review led directly to the technical objectives of the research (Section 2.2.2). In fulfilment of Objective 6, a number of appropriate techniques employed to visualise ARS data in other disciplines were presented along with their potential for archaeological feature detection, contributing directly to the methods used to analyse ARS data in this study (Chapter 6).

3 Aim and Objectives

3.1 Aim

The aim of this research is to assess the full information content of airborne laser scanned and digital spectral data (referred to jointly here as Airborne Remote Sensing or ARS data) with respect to identifying archaeological remains in non-alluvial environments. A range of techniques will be systematically analysed to establish how this information can best be extracted and utilised.

3.2 Objectives

The objectives of this research are based on the gaps in current knowledge identified through the review of current literature (Chapter 2). While an assessment is made of the potential of ARS to contribute to our understanding of the historic environment in non-alluvial environments, the objectives are predominantly technical in nature covering an assessment of techniques for processing ARS data and the impact of external factors such as seasonality and soil moisture.

- Objective 1. To review archaeological applications of ARS, focusing on the current state of research in an international context and identify the potential value of the information collected by ARS for understanding archaeological sites and features in grass-dominated environments in the UK.
- Objective 2. To identify a representative case study in a grass-dominated environment where there are a range of archive ARS sources available and a comprehensive study of vertical and oblique archive archaeological photography has already taken place.
- Objective 3. To assess the relative value of ALS and digital spectral data when compared with other remotely sensed data, including the transcription of archive aerial photography undertaken by the National Mapping Programme and modern military vertical 4-band aerial photography.
- Objective 4. To contribute to our understanding of the impact of environmental conditions on archaeological site detection using ARS data in grass-dominated environments (with specific focus on season of acquisition and soil moisture content).

- Objective 5. To assess the value of ARS data for providing quantitative information regarding archaeological feature type and status, degradation and preservation.
- Objective 6. To survey existing technical literature to find appropriate processing techniques from other disciplines that may be of benefit to the archaeological analysis of ALS and digital spectral data.
- Objective 7. To assess sensitivity across the wavelengths recorded by digital spectral data in order to identify whether some regions of the spectra are more useful for detecting archaeological features than others.
- Objective 8. To analyse current 'standard' and advanced procedures for visualising ARS data with regard to their impact on the visibility of archaeological features grass-dominated environments.
- Objective 9. To develop a method of assessing the accuracy of ALS models over microtopographic features and thus provide a means by which to compare them quantitatively.
- Objective 10. To evaluate the potential of ALS intensity to provide additional information about archaeological features.
- Objective 11. To quantify the relationship between ALS intensity / digital spectral data and standard geophysical prospection techniques through simultaneous acquisition of terrestrial survey data.
- Objective 12. To assess the value of digital integration of remotely sensed datasets for improving archaeological feature recognition.

4 Case Study Selection

4.1 Introduction

This chapter gives the rationale for case study selection, as determined from the preceding review of current literature (Chapter 2) (section 4.2) and introduces the areas investigated for the study (section 4.3). The selected areas are presented in terms of their location, geology, past and present land use; providing background to the use of airborne remote sensing techniques (section 4.3). In section 4.4 the nature of the known archaeological features in these areas is also discussed, as are previous investigations, providing context for the archaeological aims of the current research.

Following on from this, Chapter 5 gives detail of the specific locations of airborne and terrestrial survey for each of the study areas that formed this project.

4.2 Case Study Rationale

The rationale for the selection of study areas can be divided into two equally weighted sets of drivers; those that are related to the archaeological aims and practicalities, and those that centre on issues of data availability and quality.

Archaeologically, a review of the existing literature strongly indicates that there is a gap in understanding regarding the application of remote sensing techniques for archaeological prospection in the UK outside alluvial terraces dominated by intensive arable regimes (section 3.6). In total arable land use accounts for 25.5% of land cover in the UK (Morton et al. 2011). The primary archaeological driver for site selection was therefore the identification of landscapes of archaeological interest that were not currently under an arable regime. Grassland was chosen as the target environment as it represents the largest category of land cover in the UK at 38% (Morton et al. 2011). Grassland is also of strategic importance as this land cover tends to typify the areas that lie between landscapes dominated by arable farming and the dense moorland vegetation typical of higher altitudes in the UK. Lying at the margins of sustainable agriculture, and therefore more readily affected by changes in climate than lower altitudes, these areas contain a wealth of information about changing subsistence strategies through the prehistoric and historic periods. Additionally many of the extensive grasslands in the UK fall within National Parks and are designated for their natural beauty and the value of their geology, ecology and historic environment and this designation is reflected in their modern land use patterns which are dominated by pasture and recreational use. Consequently, although not subject to the industrial-scale agriculture of lower lying regions, many grassland environments

are under pressure from changes in land management, tourism and environmental and ecological change that impact on management of the historic environment.

The application of ARS data also required study areas that were rich in features of varying types and states of preservation, to test the techniques over as representative a selection of archaeological features as possible. To ensure an accurate baseline measure of these features it was also important that the areas had an investigation history that included aerial photography, excavation and geophysical survey. Finally, the study areas also needed to be easily accessible for ground observations.

The second set of drivers determining the choice of site was the availability of high quality archive remote sensing data. This should include as a minimum one ALS and one digital spectral dataset of the same geographical area. For preference the archive for the area should include a number of different sensors with data of different acquisition dates. The potential for bespoke data acquisition should be considered but, in accordance with most archaeological uses of these types of data, it was envisaged that the foundation of the research would be based on archive data. Consequently the quality of data, both in terms of spatial and spectral resolution and available metadata, has to be ensured to maximise the potential of the data for archaeological research.

In summary the case study areas needed to:

- be currently categorised as an area of grassland
- have a variety of known archaeological features
- have a history of previous archaeological study
- have a number of high quality airborne datasets from a variety of sensors
- be accessible both for ground observations and potential further airborne survey

4.3 Salisbury Plain

Balancing the factors listed above was a complex task, however Salisbury Plain Training Area (SPTA) in Wiltshire met both the archaeological and archive data requirements. SPTA is managed by Defence Estates (the land management arm of the Ministry of Defence) for military training purposes and is divided into three ranges known as (West, Central and East) by the north-south A345 and A360. The West and Central ranges are subject to very heavy military activity and live firing while the East Range is used less intensively for terrestrial manoeuvres but is the site of much airborne military activity with Upavon Airfield and a number of

parachute drop zones.

Due to the significance of the natural environment over 20,000ha of the chalk grassland is protected as a Site of Special Scientific Interest (SSSI) and a Special Area of Conservation (SAC). To facilitate access, the two study areas selected, Everleigh and Upavon, lie in the East Range. Precise details of their location and extents are detailed in sections 5.2.1 and 5.3.1 (figure 4.1).

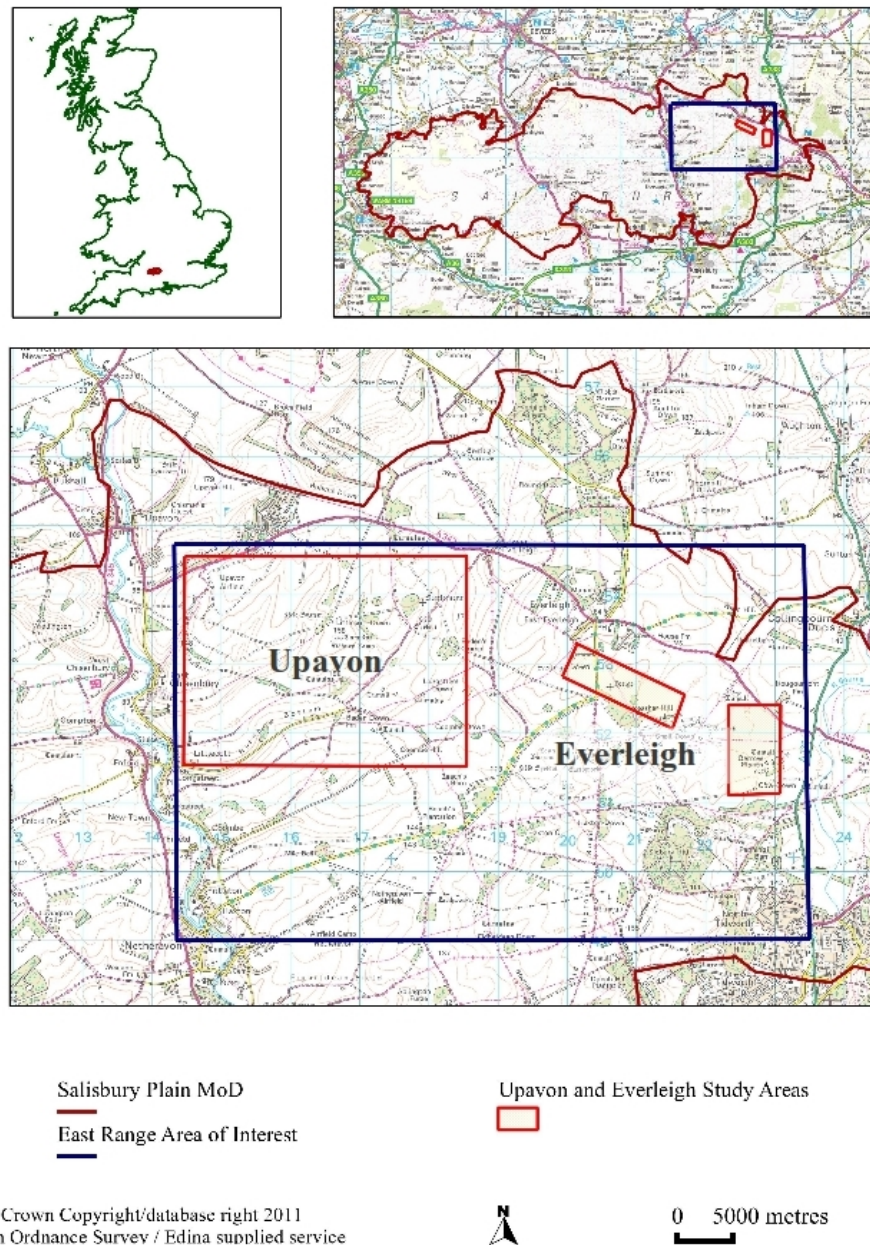


Figure 4.1: Location map of the Salisbury Plain Study Areas

4.3.1 Location, Geology and Land Cover

Salisbury Plain is an area of approximately 39,000ha of marginal grassland in Wiltshire, England that lies on Upper and Middle Chalk, with rare outcrops of Clay with Flints, most notably at Chriton Maggot, Upfront Down and Sidbury Hill (Entec 2003) (figure 4.1). The topography of the area is typically rolling hills and dry valleys and the vegetation is typified by extensive areas of unimproved grassland with occasional areas of woodland (both natural and plantation) and scrub. The central zone of rough unimproved grassland is surrounded by an agricultural “buffer zone” that is also owned by the Crown and provides protection to local communities from the intense military activity on higher ground. The Plain remains the largest area of natural chalk grassland in North West Europe.

4.4 Archaeological Interest

Salisbury Plain is one of the most important archaeological landscapes in the UK, described as “unique and priceless” by English Heritage (McOmish et al. 2002:1). The archaeology of the Plain is remarkable both for its location between the World Heritage prehistoric landscapes of Stonehenge and Avebury and for the outstanding preservation of its archaeological features. Purchased by the War Office following the agricultural depression of the late 19th Century (McOmish et al. 2002:6), the Plain is the last area of chalk grassland in the UK that remains predominantly unaffected by agricultural intensification. As such a palimpsest of prehistoric, Roman and Medieval features survive on the Plain, totalling more than 2300 known archaeological sites (Crutchley 2000). In brief, the monumental landscape of this area is characterised by Neolithic and Bronze Age barrows and ditch systems which intermingles with Iron Age and Romano-British settlements and field systems, many of which were identified from the air (ibid). During the 5th Century the settlement pattern shifted from the higher ground to the river valleys leaving virtually no evidence of medieval and post-medieval settlement or subsistence on the Plain itself (McOmish et al. 2002:10).

There are however, preservation challenges associated with the current land use. Military activities can conflict with preservation of sites, either through direct destruction (although this is a very rare occurrence in recent times, many barrow features bear witness to WWII tank activity) or by preventing frequent grazing and thus encouraging the encroachment of scrub. In the East Range, where agricultural activity has been more commonplace into the 20th century, a range of states of preservation can be identified in features such as field systems that cross the landscape.

4.4.1 Previous Archaeological Investigations

In addition to the variation in preservation of the upstanding archaeological features, the Plain has been selected for this study due to the quality of previous and on-going investigations, which have characterised the nature of the archaeology through aerial survey, DGPS derived topographic survey and geophysical survey, providing a baseline for current research.

Although there was some antiquarian interest in the monuments of the Plain in the late 19th and early 20th Centuries, for much of the last Century very little work was undertaken in comparison to other areas of the Wessex chalk. This is particularly true of the northern part of the Plain in which the study areas are located and there appears to have been an assumption, expressed by O.G.S. Crawford in the 1940s when consulting on the choice of area for the first National Parks, that the archaeology of the Plain was too badly damaged by military use to warrant preservation (Bradley et al. 1994:1). Only recently, and on comparison with areas such as the Marlborough Downs where the archaeological landscape has been virtually destroyed by agricultural use (Gingell 1992), has awareness grown of the unique preservation of upstanding monuments on the Plain. Consequently, archaeological investigation on the Plain has flourished in the last two decades, benefiting from improved awareness of conservation management within Defence Estates. An excellent general summary of previous archaeological investigations is contained in McOmish et al. (2002:13-18) and consequently the following section will focus specifically on investigations within the vicinity of the Everleigh and Upavon study areas in the East Range (figure 4.1).

4.4.2 Everleigh Study Area Environs

The Everleigh study area comprises a selection of evidence from almost all prehistoric periods from the Neolithic henge, Bronze Age linear boundaries and barrow cemeteries, through the remains of Iron Age and Roman-British agricultural systems (figure 4.2). In addition there remains little evidence of subsequent land use, with the exception of a single medieval enclosure (SU2015 5317) and pond of likely post-medieval date (SU 2065 5293).

The first recorded excavations in the Everleigh study area were of the Snail Down Barrow cemetery between 1954 and 1957 (McOmish et al. 2002:17) the excavation by Charles and Nicholas Thomas (Thomas et al. 2005) is one of the most complete investigations of a Bronze Age burial monument group and was significantly augmented by the contemporary landscape work of Colin Bowen (Bowen 1978). The conclusions of this work formed the foundation for two later studies in the area, the first based on prehistoric boundary features (Bradley et al. 1994), the second examining the Iron Age and Roman development of the area (Fulford et al.

2006).

The Wessex Linear Ditches Project was begun in 1988 with the aim of providing an informed assessment of the nature of the linear ditch systems of the area, and in doing so investigate the pattern of Bronze Age and Iron Age settlement at a landscape scale (Bradley et al. 1994:6). The function of the linear ditch systems (often referred to in earlier literature as “ranch boundaries”) and their connection to “celtic” field systems and other archaeological features has been viewed as critical to the understanding of the development of settlement, land use and cultural identity in the later prehistoric periods, despite the marginal nature of the chalk landscape (ibid:5). In the locality of the study area, this project undertook a number of excavations across the extant ditches and banks which through detailed examination of the stratigraphic, environmental and pottery sequences revealed the complexity of Bronze Age landscape division. Around Sidbury Hill the initial linear ditches were dated to the Middle Bronze Age when the hill and its environs appear to have been relatively peripheral to the general pattern of land enclosure (Bradley et al. 1994:132). Later in the Bronze Age, Sidbury Hill with its convergence of linear features appears to have become the centre for a reorientation of settlement and land division, with evidence for reworking and recutting of the ditches (ibid:133). Little evidence for the contemporary settlement pattern in the area was recovered by this project due to the unsuitability of the pasture fields for surface collection techniques (Bradley et al. 1994:113); although evidence of early Bronze Age settlement was uncovered during the excavation of the Snail Down barrow cemetery (Nicholas 2005:157). In the Everleigh area, later prehistoric lynchets were seen to respect the Bronze Age linears and enclosures formed by them, giving grounds to the suggestion that by the Early and Middle Iron Age the earthworks were being used to distinguish zones of pasture in an otherwise intensively cultivated arable landscape (Bradley et al. 1994:135).

The Iron Age and Romano-British landscape and settlement patterns around Everleigh were explored more fully by Fulford et al. (2006) in a study that examined the extent and context of the intensive agricultural exploitation of the Plain during this period. The intensification of production during this period as evidenced by the ubiquitous “celtic” field systems is a phenomenon that stands in stark contrast to earlier and subsequent use of the Plain, whose typically poor soils and lack of natural water resources appear to have limited agricultural exploitation (ibid). Within the study area the enclosure at Everleigh (SU 207 525) was targeted for limited excavation which revealed the enclosure ditch as 2m wide and 1.5m deep but found no evidence for a bank. Occupation was dated to the Early Iron Age, with possible Bronze Age origins intimated by the presence of Late Bronze Age pottery, and the absence of diagnostically Middle Iron Age pottery indicated early abandonment (Fulford et al. 2006:41-2). The area of rectangular platforms and hollows recorded by RCHME at grid location SU 2099 5253 were also examined by test pitting to investigate the hypothesis that they represented the remains of an open settlement aligned along a hollow-way and abutted by the surrounding field system (ibid:41). No artefactual or structural evidence of this was revealed but the Late Neolithic / Early Bronze Age pottery that was recovered was attributed to the proximity of the henge monument at SU 2064 5260.

Although there was no investigation of the lynchets in the study area, excavations of a comparable system on Weather Hill, 750m to the south recognised two phases of cultivation with the first dated by the pottery assemblage to the 1st and 2nd Centuries AD and the upper layers of the lynchets to the 3rd and 4th Centuries AD (Fulford et al. 2006:90). The test pits recorded no associated ditches but did note some possible boundary features in the presence of stake and post holes (ibid). Molluscan evidence indicated typical arable conditions within an open country setting (Allen in Fulford et al. 2006:150).

In summary, the archaeology of the Everleigh study area is typified by the substantial remains of Iron Age -Romano British field systems. These lie adjacent to and respecting a Neolithic – Bronze Age ritual and domestic landscape identified through a henge monument, linear ditch systems and barrow cemeteries. Despite the Everleigh area lying on the edge of the Salisbury Plain, and therefore at the margin of the modern agricultural zone, there is little evidence of Medieval or Post-Medieval interaction with the landscape leading to remarkable preservation of upstanding monuments from earlier periods.

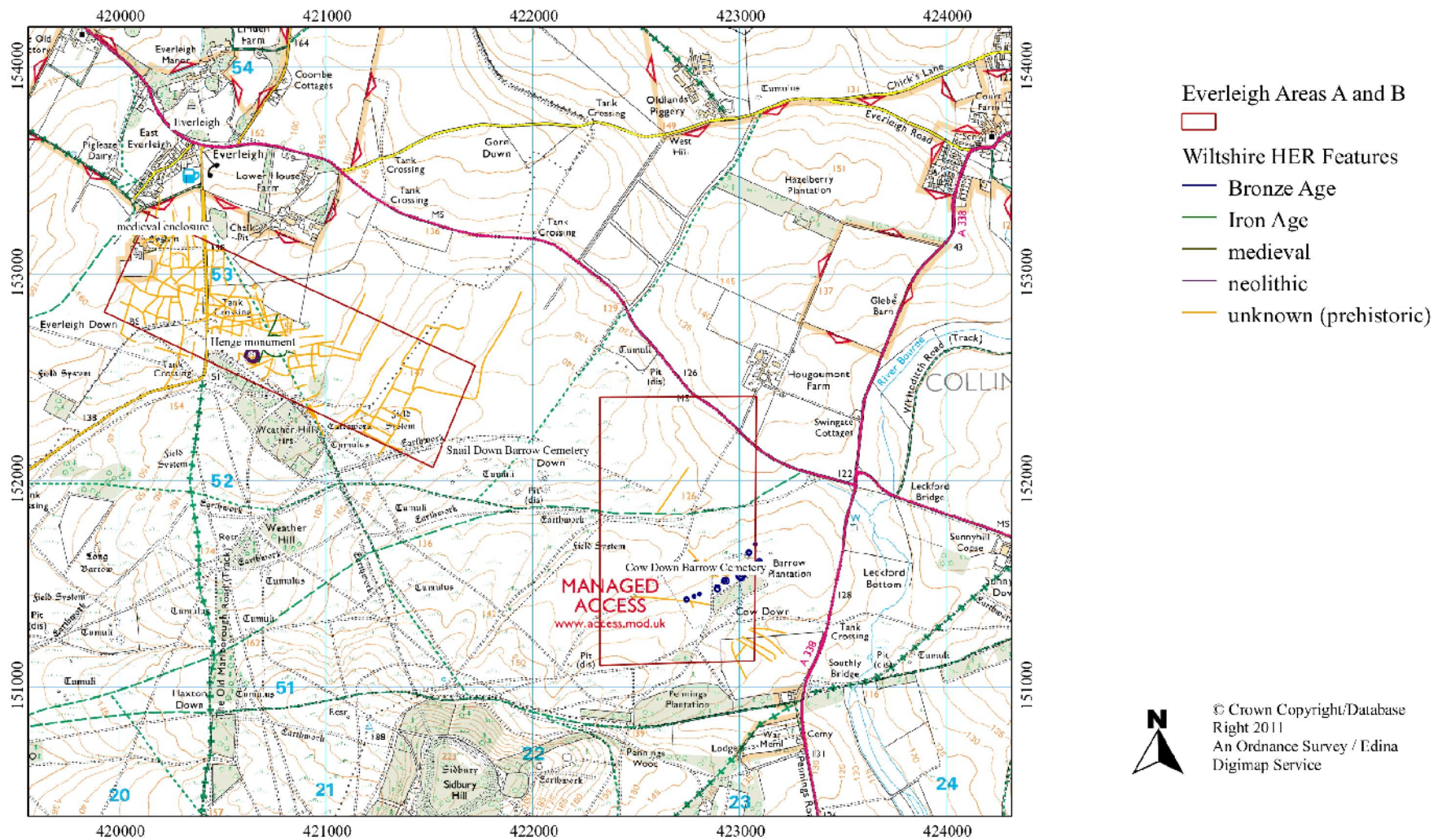


Figure 4.2: The Wiltshire Historic Environment Record for Everleigh Study Areas A and B

4.4.3 Upavon Study Area Environs

The Upavon study area (figure 4.3) was selected to lie within the Western Sample Area of the Iron-Age and Roman-British Settlements of the Salisbury Plain Project which ran from 1992-5 and examined in detail through surface collection and excavation the extensive remains of this period in the East Range of Salisbury Plain (Fulford et al. 2006). The archaeology of the Upavon area is typified by well preserved Romano-British sites and field systems but also has substantial remains of “Celtic Fields” and funerary monuments (Fulford et al. 2006)

Fieldwalking and ditch sections during the Iron-Age and Roman-British Settlements project produced residual evidence for Neolithic and Bronze Age pottery although the small quantities recovered make it difficult to relate the scatters to permanent settlement (Fulford et al. 2006:197). Open settlement in early prehistoric periods is likely to have been typical but is almost impossible to detect. The earliest settlement evidence in the Upavon study area comes from the earliest phases of Chisenbury Midden (SU 1462 5324) where chalk floors indicate late Bronze Age / Early Iron Age occupation (McOmish 1996) and the enclosure at Lidbury Camp (SU 1665 5335) which has been dated to the Later Bronze Age (Cunnington and Cunnington 1917). From the limited excavation of the latter site, it appears likely that the enclosure represents seasonal occupation associated with sheep husbandry rather than permanent occupation (McOmish et al. 2002:155).

The beginnings of Iron Age enclosure in the 7th-6th Centuries BC can be traced to enclosures at Coombe Down South (SU 1925 5201) and Everleigh (SU 207 525). In the Middle Iron Age these were followed by enclosures at Chisenbury Field Barn (SU 1585 5348), Coombe Down North (SU 1846 5235) and two banjo enclosures at Beach's Barn (SU 1898 5098). With the exception of Everleigh, occupation appears to be continuous at these locations throughout the Middle Iron Age (ibid).

The late Iron Age settlement pattern is described as discontinuous, with the general abandonment of enclosures on the higher ground and an apparent shift to nucleated settlement in the river valleys. The Iron Age Romano-British village at Chisenbury Warren (SU1781 5376) which is often thought of as the type-site for linear rural settlement of the Romano-British period, has its origins in this period but the bivallate enclosure at Coombe Down South also shows continued occupation through the late Iron Age and into the Romano-British period (Fulford et al. 2006:199). Environmental evidence suggests an increase in both cereal cultivation and animal husbandry in the area during the Iron Age (Bradley et al. 1994:120-1), but evidence of loom weights, combs and spindle-whorls also hints at some textile manufacture in the settlements, along with iron working at Coombe Down (Fulford et al. 2006:200).

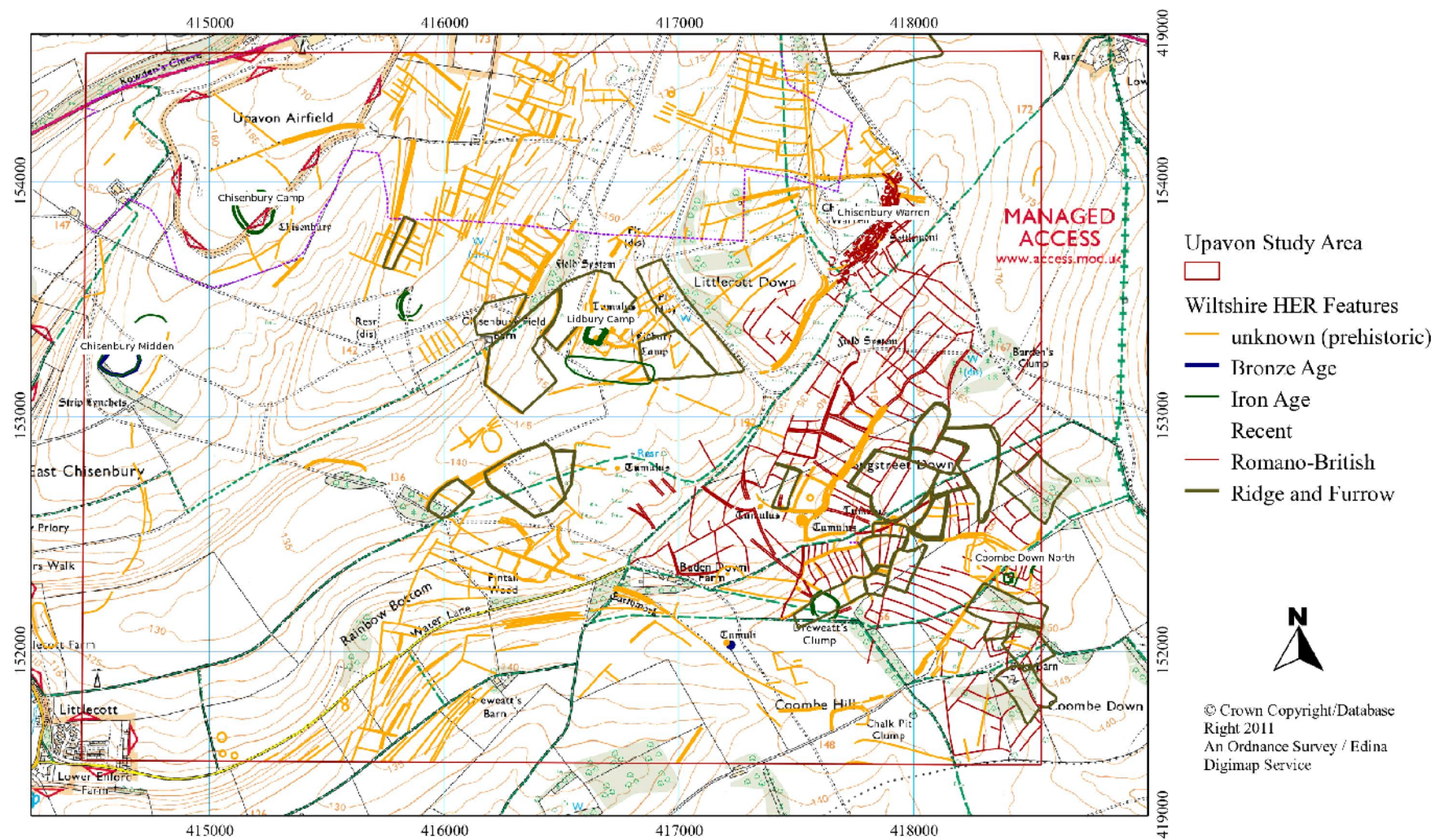


Figure 4.3: The Wiltshire Historic Environment Record for the Upavon Study Area

Evidence of social and ritual life in the Iron Age can be found in the continued use of Chisenbury Midden (SU 1462 5324) likely to be associated with the nearby bivallate hillfort Chisenbury Camp (SU 1519 5387) which was levelled in 1931.

Defining the transition from Iron Age to Romano-British settlement in the Upavon area is difficult, largely due to uncertainty and longevity of pottery chronologies in the 200 year period from the 1st Century BC through to the 1st Century AD (Fulford et al. 2006:201). This problem is illustrated in the earliest phases of the Chisenbury Warren settlement where there is conflicting evidence from radiocarbon dates and pottery assemblages in the earliest contexts (ibid).

Generally the larger nucleated “villages” like Chisenbury Warren are interpreted as low status settlements on the higher ground, while smaller “villa” settlements of the Avon valley are seen as higher status, privately owned houses and estates (Fulford et al. 2006:203). Indeed it seems that the predominance of Chisenbury Warren and other linear settlements of this period on the Plain is much more to do with their outstanding preservation than their original importance (McOmish et al. 2002).

Investigations of the expansive field systems around Coombe Down, Longstreet Down and Chisenbury Warren show that most of the lynchet formation took place in the Romano-British period. Of those excavated as part of the Iron Age and Romano-British Settlements project, only the field system near Chisenbury Warren showed any evidence of Iron Age origins (Fulford et al. 2006). The monumental evidence for extensive and long-lived landscape management indicates an intensification of agriculture at this time, but faunal and palaeoecological evidence suggest that there was continuity of Iron Age practises of animal husbandry and cereal cultivation (Fulford et al. 2006:206). In addition, lack of typical building materials and portable material culture are seen as evidence of a lack of engagement with wider markets, indicating that though agriculture intensified in the Romano-British period, productivity may still have been comparatively poor (ibid). These indications of a “subsistence-only” lifestyle is supported by age-at-death statistics for the faunal collections and an apparently higher than average infant mortality at Chisenbury Warren. A complementary hypothesis is that in the case of Chisenbury Warren this lack of material wealth may also be explained by a loss of produce to an estate owner and this too may be supported by the lack of continuation of settlement into the post-Roman period (Fulford et al. 2006:218).

Land use on Salisbury Plain is typified by a general lack of cultivation in later periods leading subsequently to its purchase by the military (McOmish et al. 2002:12-13) in the 19th Century, which poses the question of why the Romano-British period saw such intensive cultivation of this relatively unproductive region. Aside from a small climatic optimum known at this time, historical evidence suggests that the Plain was only cultivated during times of high population

and increased cereal prices, such as during the Napoleonic wars. Increased demand for grain to supply the Roman military and urban centres along with improved transport links are suggested as driving economic factors in the expansion of agriculture at this time. It is also considered that social factors, including population displacement and expansion as indicated by the nucleation of settlement at the end of the Iron Age, may also have played an equally important role in shaping the landscape.

In summary the archaeology of the Upavon study area is typified by the remains of nucleated rural settlement and agricultural intensification with its origins in the Bronze Age but predominantly belonging to the early centuries of the 1st Millennium AD (Figure 4.3). As with the Everleigh area, there is little evidence of later land use across the area, with only isolated areas of Medieval ridge and furrow earthworks, lending the Upavon area its character as a well-preserved later prehistoric landscape.

5 Data

Having established the selection rationale and background to the Everleigh and Upavon study areas in Chapter 4, the details of the origin and specifications of all the data used for each of the study areas were collated. Any preprocessing of these data that was not specifically related to the objectives of the research has been detailed in this chapter.

The following chapter is divided into four sections covering the data collated. The first of these (section 5.1) covers the archaeological data in the form of local and national geospatial records along with published research and grey literature. Section 5.2 describes the various archives used to collect archive ARS for the Everleigh study area. The details of the acquisition of ALS and hyperspectral data by the Natural Environment Council Airborne Research and Survey Facility (NERC ARSF) to the project's specifications are given in section 5.3 followed by a summary of the data collected by the field survey in the Upavon study area (section 5.4).

5.1 Archaeological Data

5.1.1 Existing Archaeological Record (Everleigh and Upavon)

The areas selected for this research were relatively well-studied with a number of published research projects exploring the prehistoric and Roman landscapes (Bradley et al. 1994; McOmish et al. 2002; Fulford et al. 2006) alongside unpublished reports (Crutchley 2000; Thruston and Cohen 2005). The available data is summarised in table 5.1.

Data Type	Format	Description
National Monument Record	Database output / Shapefiles	Information about archaeological monuments and previous fieldwork collected by the NMR, Swindon. Scheduled monument records.
Wiltshire County Historic Environment Record	Database output / Shapefiles	Information about archaeological monuments and previous fieldwork collected by the HER, including digitised air photograph transcription.
Published Resources	Monographs	English Heritage Field Survey (<i>The Field Archaeology of the Salisbury Plain Training Area (2002)</i>) Excavation Reports (<i>Snail Down, Wiltshire: The Bronze Age Barrow Cemetery and Related Earthworks (2005)</i> ; <i>Prehistoric land divisions on Salisbury Plain(1994)</i>)
Unpublished Resources	Grey literature	Defence Estates yearly condition monitoring reports, Defence Estates Remote Sensing Assessment Report, (2003; 2005) Salisbury Plain Training Area - A report for the National Mapping Programme (2000)

Table 5.1: Archaeological Resources for the Salisbury Plain Study Area

The spatial data available comprised two datasets; the National Monuments Record (NMR) and the Wiltshire Historic Environment Record (HER). Both of these contain information on previous archaeological interventions (Events), archaeological features (Monuments) and scheduled monuments (Designations). On comparison it became clear that the Wiltshire HER record was the most detailed spatial dataset for archaeological features and that the NMR recorded no additional features for the study areas. This is due in large part to the incorporation of the results of the National Mapping Programme (NMP) transcription of archive aerial photographs (Crutchley 2000) into the HER dataset. Consequently the HER was selected to provide the archaeological spatial baseline for the study

5.1.2 Preprocessing of the Wiltshire HER Data

The Wiltshire HER data were provided in the form of both a shapefile and an MS Access database. Initial quality checking of these data ensured that each form was consistent with the other, e.g. that the records in the shapefile matched those in the database and vice versa. During this process a number of inconsistencies were discovered and rectified.

To allow consistent mapping across feature types it was also necessary to simplify some features from the complicated topology exported from the HER system. For example, barrows that were mapped as many concentric rings were simplified into entities that matched their physical form, i.e. in the case of a simple round barrow one polyline was drawn tracing the ditch and one enclosing the mound. Figure 5.1 shows the simplification from the original HER record (left) which included multiple polylines representing a symbology used to record the banks and ditch of the henge (PRN 8404) and an additional polyline (PRN 10061) outlining the scheduled area, to the simplified spatial record (right) of two polylines, one for the internal ditch and one representing the external bank. The spatial location of the feature has also been revised from the more accurate ALS-derived image.

The simplification process ensured that the number of polylines in the shapefile became a reflection of the features present and their topographical elements rather than the detail to which some features had been mapped (as this was found to be inconsistent across the dataset) or a product of the transformation from polygon to polyline data. This is important to allow quantitative comparison both of feature numbers and of feature length.

It also became clear that the unique identification numbers, (Primary Record Numbers or PRNs), ascribed to the HER features would not suffice as identifiers for this research, as in many cases they represented grouped or parent records rather than individual features. A case in point are the field systems across the study area that are recorded in the HER under a single number but consist of many lynchet features (figure 5.2). For the purposes of the pilot study,

each feature required a unique identifier (UID) for cross referencing, so a new “UID” field was added to the spatial data. Consequently all the HER features have both a PRN and a UID reference.

For the Upavon area it was necessary to standardise the spatial location of a number of features represented in the HER based on the information contained in the high resolution ALS model as they were found to be displaced by between 5m and 15m compared with the higher accuracy ALS model. This level of inaccuracy of features mapped from aerial photographs is not uncommon, especially in areas with few ground control points such as in the study area. Each feature that was corrected was labelled as such in its attribute table. Known features that were not visible in the ALS data were also flagged in the attribute table. Finally new records were created for features seen in the ALS data that were not recorded in the HER.

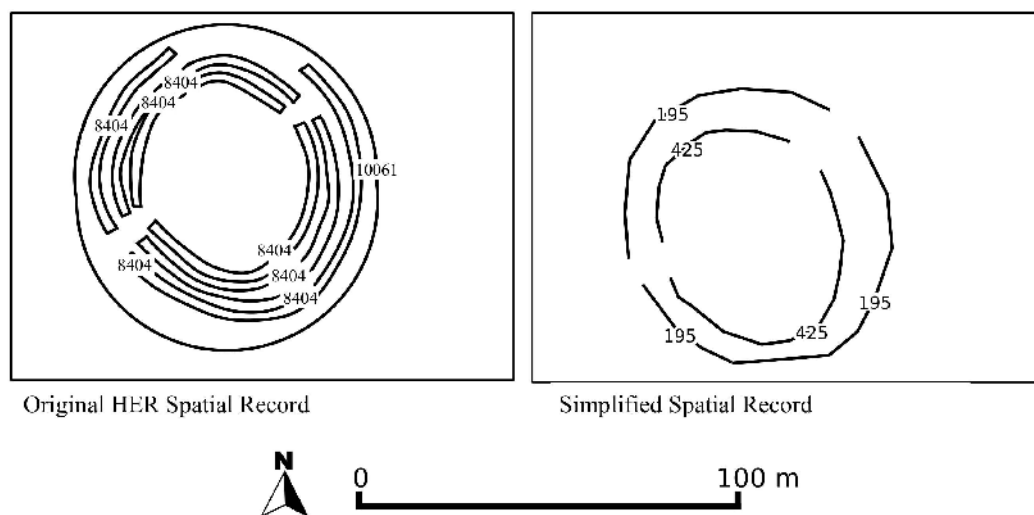


Figure 5.1: Simplifying Historic Environment Record symbology to better represent archaeological features

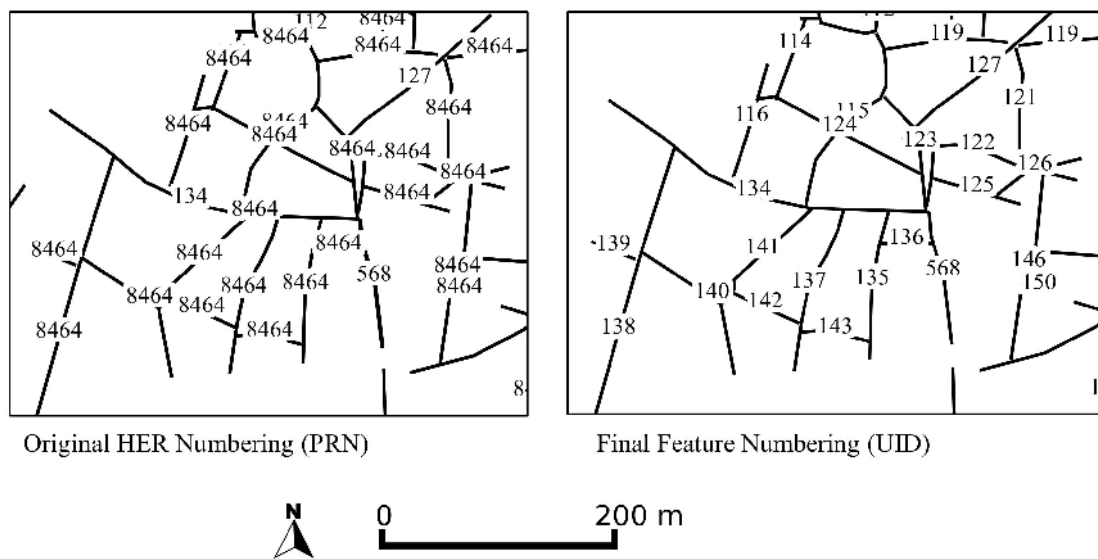


Figure 5.2: Assigning unique identifiers (UID) to features grouped by a single Primary Record Number (PRN) in the Wiltshire Historic Environment Record

5.2 Archive ARS Data (Everleigh)

Having established the archaeological significance of the study areas, it was necessary to establish the nature of the archive ARS data available to the study. The Everleigh study area was selected principally due to the availability of archive airborne datasets and additional archaeological resources and these are presented below, with table 5.3 detailing the remotely sensed data available.

Data Type	Resolution	Details	Date Flown	Source
CASI multispectral data	2m	~440-981nm	27 th April 1996	NEODC ⁶
	1.5m		7 th January 2001	EA
	1.5m		18 th May 2001	EA
ATM multispectral data	2.5m	420-1300nm	1 st June 2002	NEODC
ALS data	2m	Optech ALTAM 1205	25 th May 2001	EA
	1m	Optech ALTAM 2033	3 rd Nov2005	EA
Aerial Photography (Oblique)	0.15m		Archive (c.1950-2002)	Wiltshire HER
Aerial Photography (Vertical)	0.15m		Yearly summer coverage (2002-6)	Defence Estates
4-Band Aerial Photography (Vertical)	0.25m	Vixel Ultracam XP 580-1000nm	9 th September 2006 6 th August 2007	Defence Estates

Table 5.2: Airborne Digital Data Sources for the Everleigh Study Area

6 NERC Earth Observation Data Centre

5.2.1 *Environment Agency Multispectral Data*

The spectral data collected by the Compact Airborne Spectrographic Imager (CASI) for the Everleigh area in 2001 were purchased from the Environment Agency of England and Wales (EA). The digital spectral data for the Everleigh area was captured by a CASI sensor flown by the EA on the 7th January and 18th May 2001. The sensor was configured to supply 14 bands ranging in wavelength from 440nm to 891nm (Table 5.2). The data were geometrically and atmospherically corrected by the EA prior to acquisition by this project and no further pre-processing was applied. No metadata were available for these data so no further details are known about the exact pre-processing undertaken.

On examination of the data, it was found that while for the January flight conditions were clear, the May data was badly affected by cloud cover that obscured features in many areas. The extent of cloud coverage was also mapped to a shapefile so that the results of the feature mapping exercise could be controlled for the poor visibility in parts of the May imagery (figure 5.3). The study area was chosen to avoid the cloud cover which was worst in the vicinity of the Snail Down Barrow cemetery (SU 2184 5200), resulting in two separate areas of investigation (see section 5.2.6).

CASI Band	Wavelength Range (nm)	Mid-point wavelength (nm)	Interpretation
1	446.2 +/- 6.6	446.2	Blue vegetation response
2	470.1 +/- 6.6	470.1	Blue vegetation response
3	490.4 +/- 6.7	490.4	Green vegetation response
4	550.1 +/- 6.7	550.1	Green vegetation maximum
5	671.1 +/- 6.8	671.1	Red vegetation absorption maximum
6	683.5 +/- 4.0	683.5	Red edge
7	700.7 +/- 5.9	700.7	Red edge
8	711.2 +/- 4.9	711.2	Red edge
9	721.7 +/- 5.9	721.7	Red edge
10	751.3 +/- 6.8	751.3	Near infrared plateau
11	763.7 +/- 4.0	763.7	Vegetation reflection
12	780.9 +/- 5.9	780.9	Water absorption
13	860.2 +/- 6.8	860.2	Near infrared plateau
14	880.2 +/- 11.6	880.2	Near infrared plateau

Table 5.3: Wavelengths of the vegetation bandset of the digital spectral data supplied for the Everleigh study area

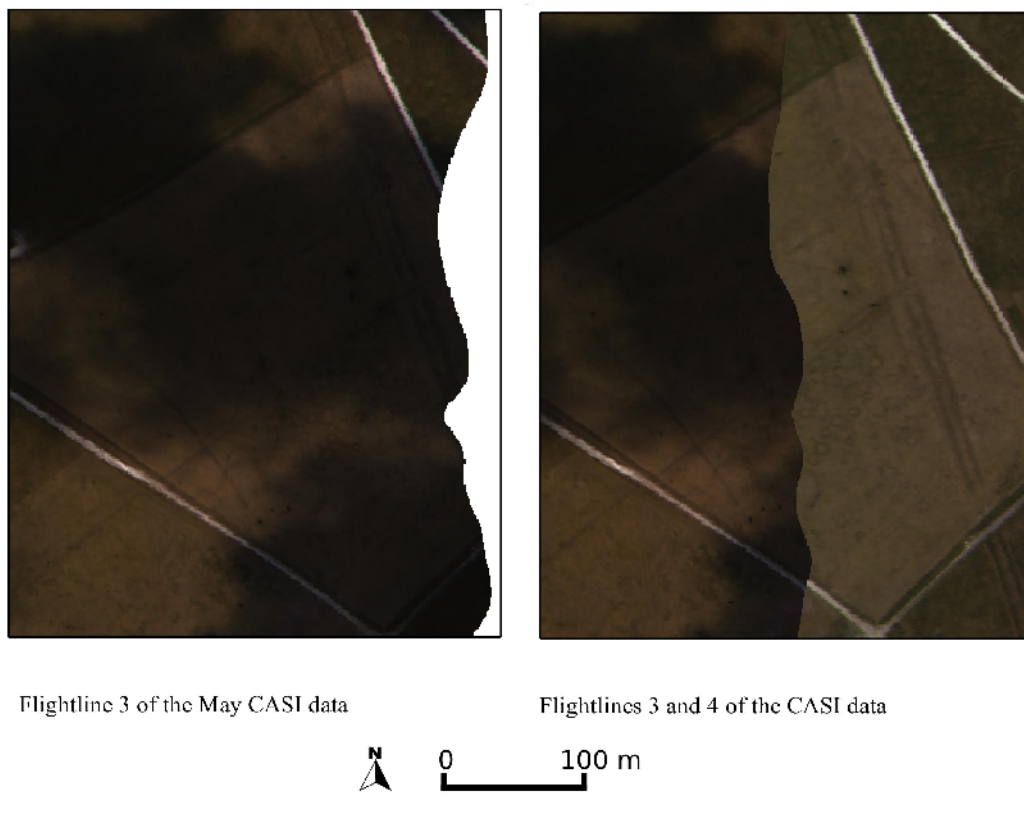


Figure 5.3: True Colour Composite showing cloud obscuring archaeological features between flightlines

5.2.2 *Environment Agency ALS Data*

The ALS data were flown by EA on November 3rd 2005 using the Optech ALTM 2033 sensor. The ALS data were supplied in the form of eight space-delimited, last return, ascii files containing x,y, z and intensity values, and were gridded to a 1m resolution Digital Elevation Model (DEM) using the last return of the laser pulse. No metadata were available for ALS survey, so original point density is unknown. The data were not filtered to remove vegetation as the Everleigh study site comprised open fields with little scrub.

5.2.3 *Historic Aerial Photography*

Wiltshire County Council supplied ESRI shapefiles and an accompanying MS Access feature database for the area from the HER. Although the HER incorporates the results of all interventions in the area, the majority of feature information is from the transcription of archive aerial photography undertaken by the English Heritage NMP project (Crutchley 2002).

The date of the photography from which the features in the HER were mapped was originally recorded in the HER (Roy Canham 2009, pers comm). This metadata would have been particularly useful to this project providing additional information on time depth and possibly the conditions under which each feature was recorded. This information would have significantly added to the interpretation of feature notes from the HER record, for example if a faint lynchet detected in the 1970s in an area of intense ploughing was not detected in the remotely sensed data from the last decade, an alternative hypothesis (that the feature has been destroyed in the interim) can be laid alongside the null hypothesis that the feature was not detectable by airborne remote sensing techniques. Additional information about the circumstances of the feature's visibility could perhaps also have been an indicator as to why it is visible or not in the current data. An example of this could be a feature that was only mapped during a particularly dry summer, leading to the hypothesis that it would not be expected to be visible in any of the contemporary remotely sensed datasets as none of these were recorded in similar conditions. Unfortunately, this type of metadata is not recorded by the NMP and consequently when the results of the Salisbury Plain NMP project were incorporated into the Wiltshire HER this potentially valuable information was lost (Roy Canham pers comm 22nd December 2009).

5.2.4 *MoD Aerial Photography*

The 4-band NIR aerial photography was given to the project by Defence Estates. The camera used for the acquisition in both years was a Vexcel UltraCam-Xp. This camera produces five channels of data from five integral sensors, but the panchromatic imagery (410-690nm) was not

available to this study (Table 5.4).

Due to time constraints and the existence of the NMP aerial survey, the decision was made to only incorporate the 2006 and 2007 Ministry of Defence vertical aerial photography in the study. It was felt that the time spent examining vertical photography from the last decade would not significantly add to the record of features in the study given the comprehensive coverage detailed in the Wiltshire HER.

Channel	Wavelength Range (nm)
Panchromatic	410 - 690
Red	580 - 700
Green	480 - 630
Blue	410 - 570
Near Infrared	690 - 1000 nm

Table 5.4: Wavelengths of the channels recorded by the 4-band vertical aerial photography.

5.2.5 NERC Earth Observation Data Centre (NEODC) Archive

The major disappointment of the archival research was the the NERC 1996 CASI and 2002 ATM datasets for the area. While the spectral data are archived and available through the NEODC, on application it became clear that no flight data had been archived for either dataset. This meant that the data could not be accurately geocorrected, rendering them inadequate for cross-data comparison as the geometric error would invalidate not only the identification of features but their shape and form.

5.2.6 Data Coverage and Sample Areas

In total an area of 4km² of the area between the village of Everleigh and Sidbury Hill was covered by EA ALS and CASI data and Ministry of Defence 4-band aerial photography (figure 5.4). Two sample areas (A and B in figure 5.5) were initially selected for a rapid assessment of the airborne data for the Everleigh area based on data coverage and quality. From the results of this assessment a smaller sub-area was selected as a representative subset for further analysis (area C in figure 5.5).

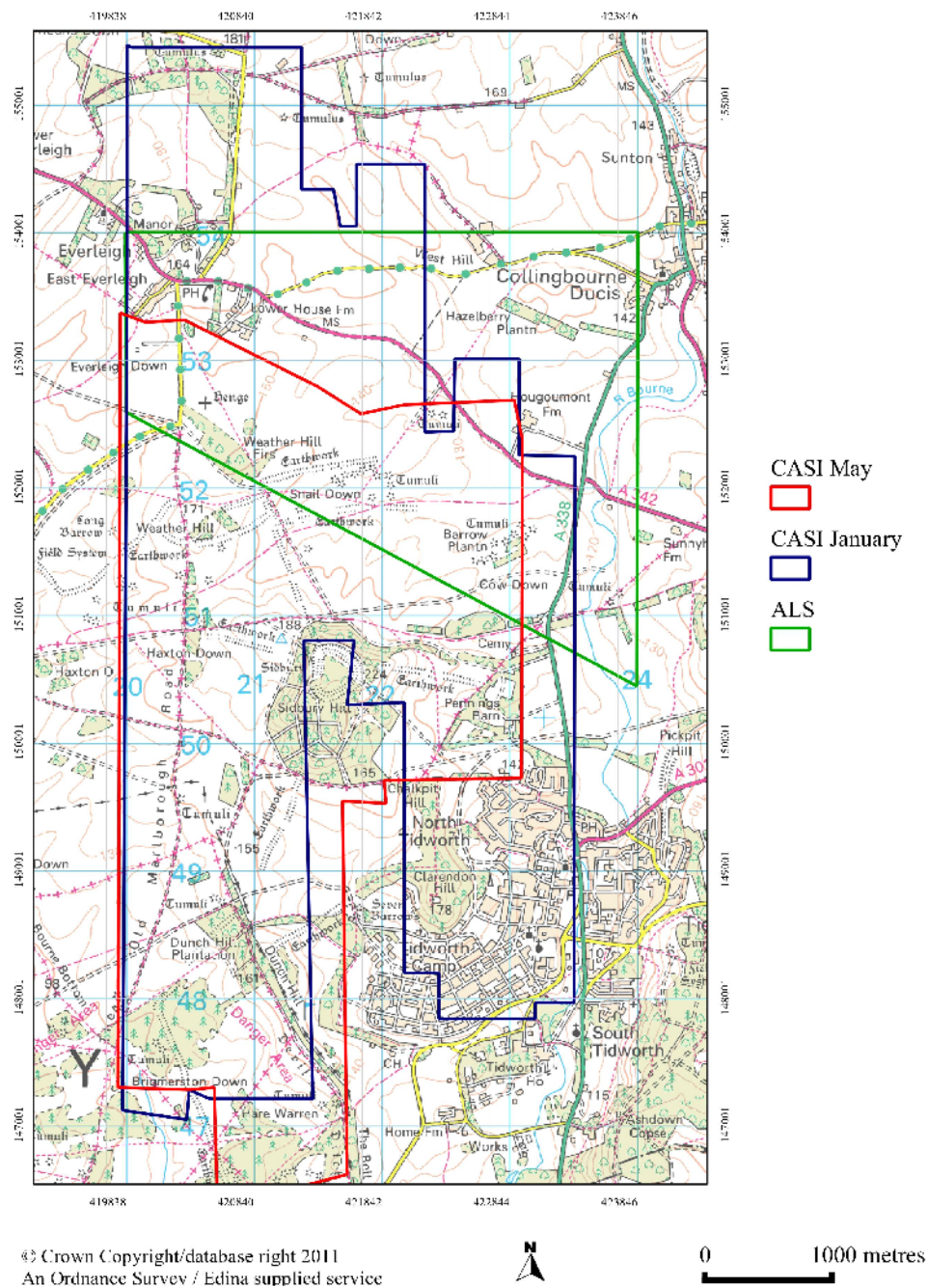


Figure 5.4: Archive airborne remotely sensed data coverage for the Everleigh Area

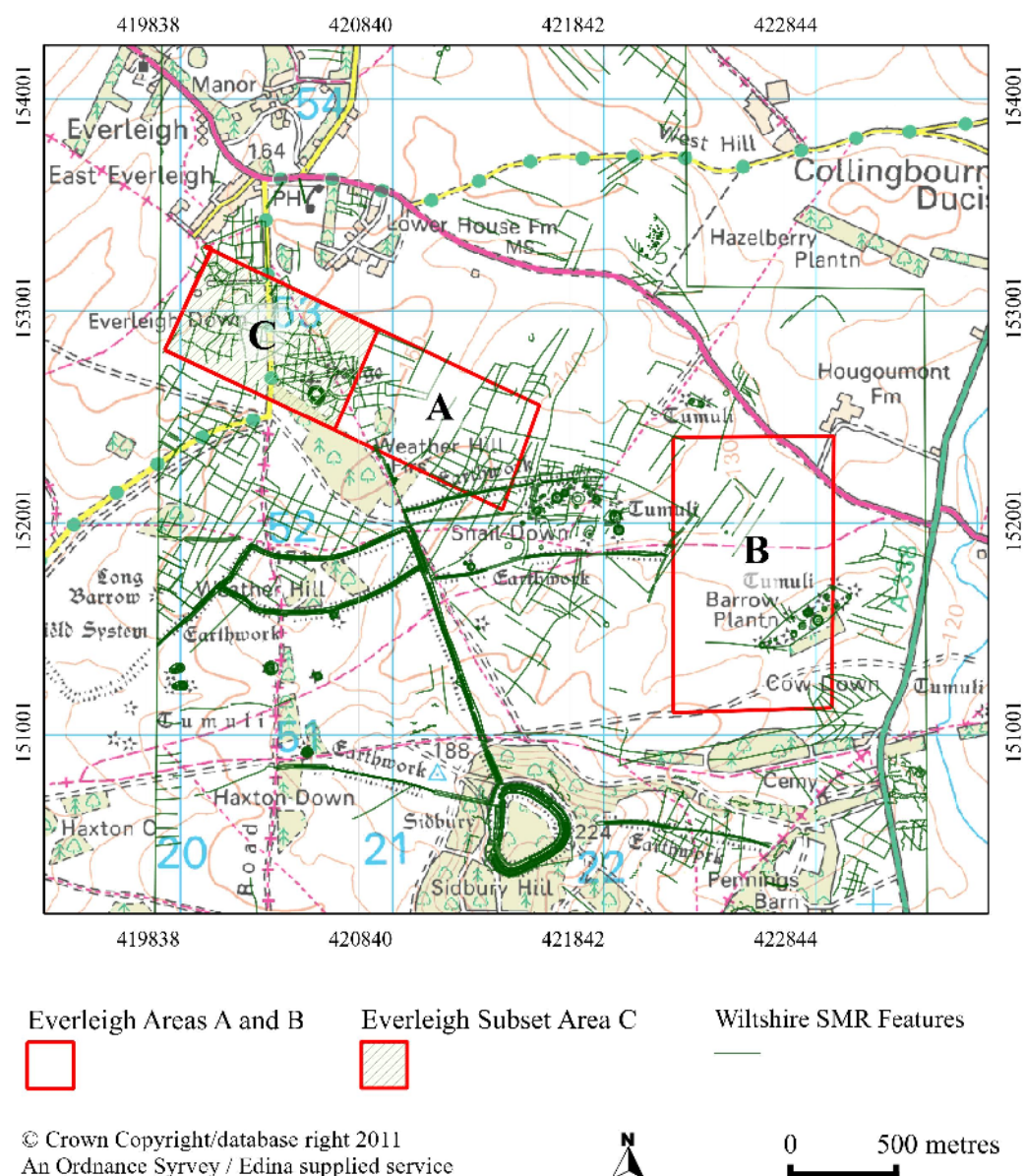


Figure 5.5: Everleigh Sample Areas A, B and C location map

5.3 Planned ARS Data Acquisition (Upavon)

A year into the research an opportunity for planned data acquisition was sought that allowed development of some of the emerging themes from the study of archive data for the Everleigh area. A successful application was made to the Natural Environment Research Council Airborne Research and Survey Facility (ARSF) for their 2010 flying season for the Upavon area. As shown in figure 5.6, the area of bespoke acquisition south of Upavon lies close to the area of the archive data study at Everleigh and as such the ancillary archaeological data are the same for both study areas (detailed in table 5.3).

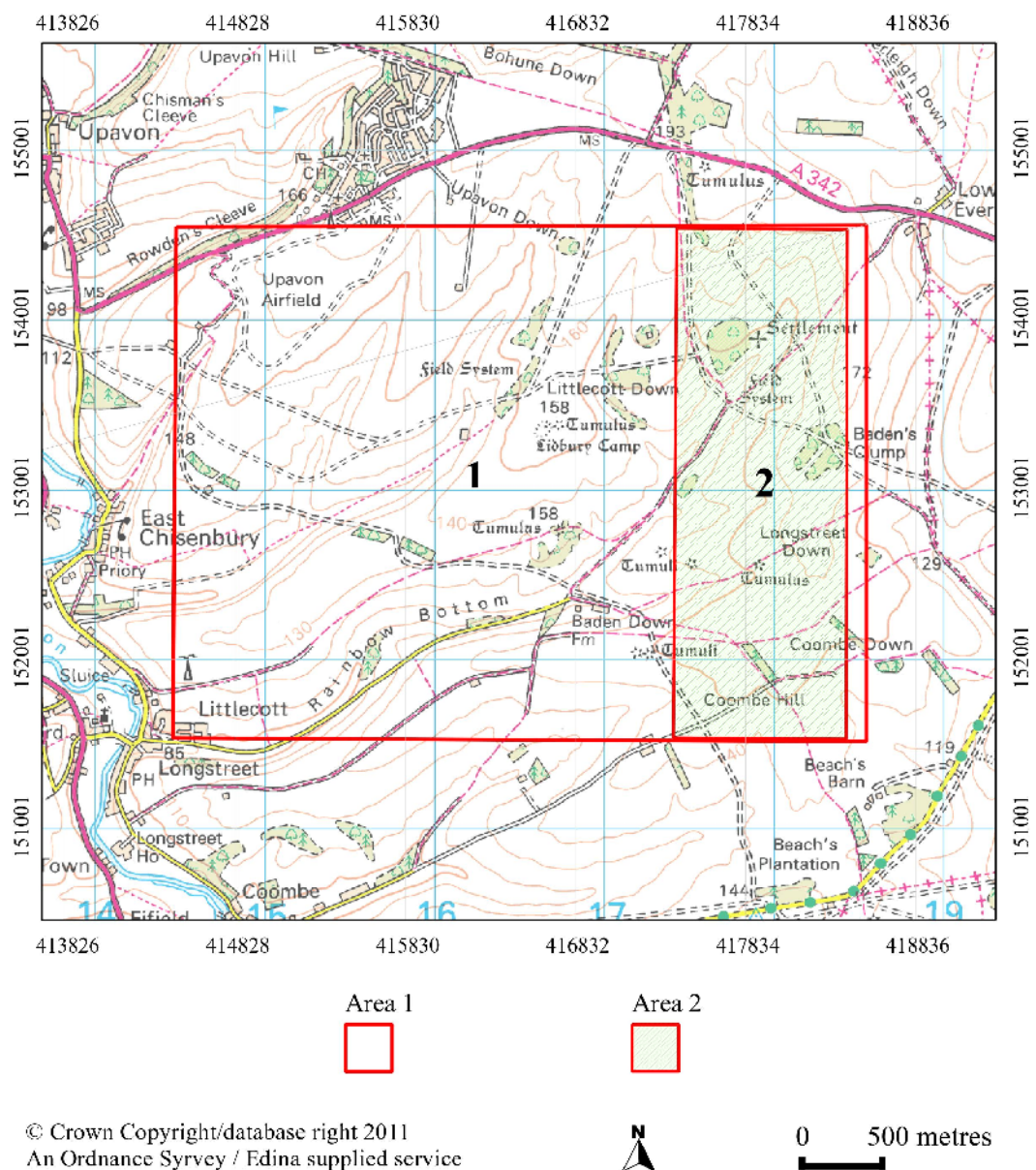


Figure 5.6: Upavon study area location map

5.3.1 Airborne Data Collection

The Upavon study area was the subject of a bespoke data acquisition by the ARSF designed to collect digital spectral and ALS data to specifications that would be optimal for archaeological research (within the limitations of the sensors currently operated by the facility). Details of the airborne data are given in table 5.5.

In total 12km² of Eagle and Hawk hyperspectral data was acquired along with simultaneous ALS survey on the 4th of March 2010⁷ (Area 1, figure 5.6). In addition a sample area of 4km² was surveyed with the ALS configured to provide the highest resolution topographical model possible within the limitations of the survey platform (Area 2, figure 5.6). The exact coverage of the high and low resolution flight lines are shown in figure 5.7.

Data Type	Resolution	Date Flown	Source
Eagle hyperspectral data	1m (400 - 970nm)	4 th March 2010	NERC ARSF
Hawk hyperspectral data	1.5m (970 - 2450nm)		
Leica ALS data (Area 1)	0.5m	4 th March 2010	NERC ARSF
Leica ALS data (Area 2)	0.25m		
Aerial Photography (Oblique)	0.15m	4 th March 2010	NERC ARSF

Table 5.5: Airborne Digital Data Sources for the Upavon Study Area

5.3.2 Spectral Data Specifications and Preprocessing

The spectral data for Upavon were collected on the 4th March 2010 using the Eagle and Hawk sensors covering the wavelengths from 450nm- 2200nm. The data were recorded as 296 bands each with a Full Width at Half Maximum (FWHM of 6.3nm). The Eagle VNIR data had a ground surface area (GSA) of 1m² and the Hawk SWIR data of 1.5m².

The spectral data were geometrically corrected using AZGCORR (Azimuth Systems 2011). It was possible to use the ALS DTM to improve the locational accuracy of the spectral data over the NextMap 10m resolution DTM. The Hawk data were resampled using nearest neighbours to 1m and combined with the Eagle data into a single file for each flightline. ENVI 4.7 was used to correct each flightline for cross-track illumination variation. The data were then atmospherically corrected using FLAASH and EFFORT Polishing in ENVI 4.7 and the results of these corrections were validated by visually comparing the spectral values from the ground targets recorded by the spectrometer. Due to the limited number and lack of spatial variation in the ground spectral samples it was not possible to use these to undertake an empirical line correction for comparison. Bands that were highly affected by water absorption were removed from the subset leaving 267 bands.

⁷ NERC ARSF flight GB10-07

Each band was checked visually for known archaeological features and excessive noise / dropped pixels. Bands that were badly affected by additional noise and pixel drop were removed from the analysis at this stage resulting in a subset file with 247 bands.

Finally an area of 1km² covering Upavon Field Site 1 (section 5.4.1) was mosaicked using ENVI 4.7 without colour correction or feathering.

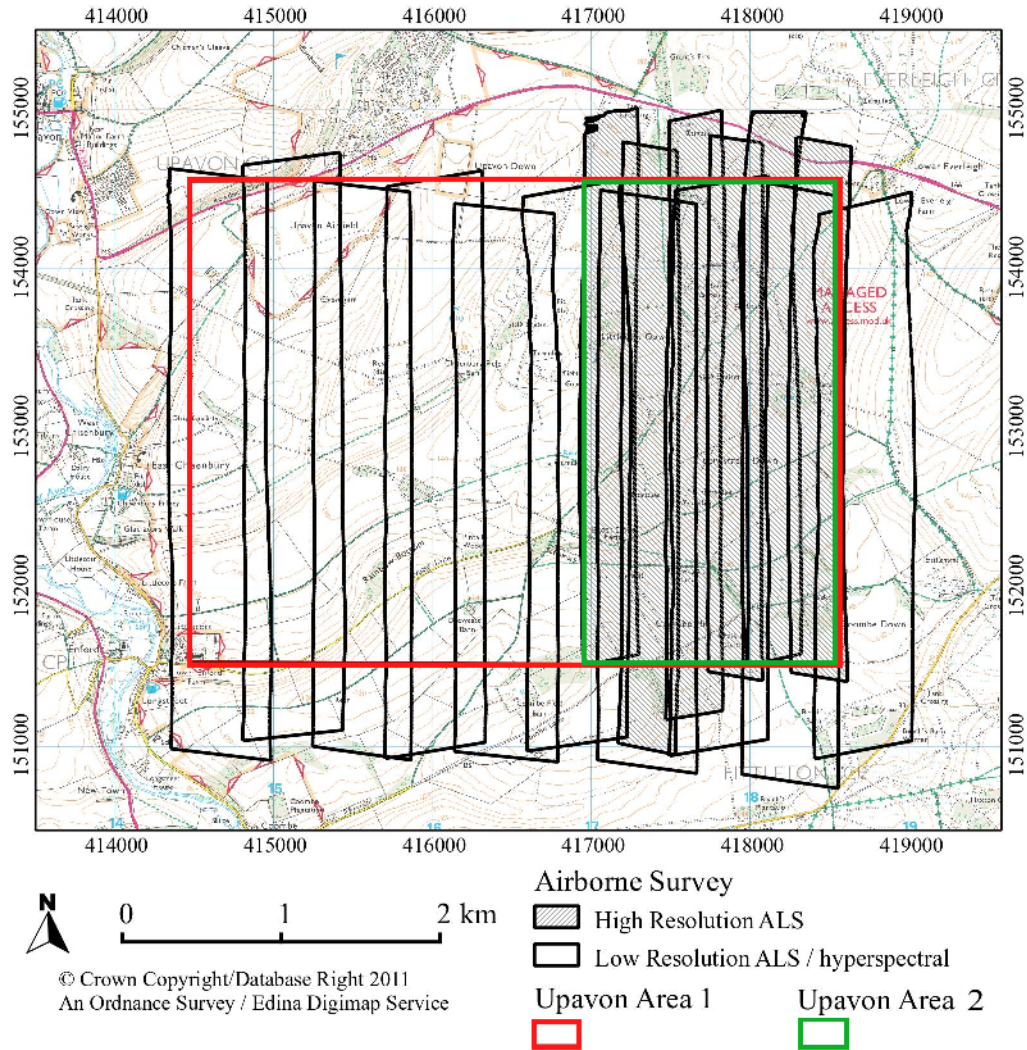


Figure 5.7: Area of ALS data collection, Upavon

5.3.3 ALS Specifications and Preprocessing

The ALS data for Upavon was collected using the Leica ALS50 at a height of 1200m on the 4th March 2010. The sensor was flown in tandem with the hyperspectral sensor for a total of 10 flightlines (Area 1, figure 5.7). An area of 1.5km by 3 km was re-flown with the ALS sensor optimised for point density (Area 2, figure 5.7).

The data were supplied as ascii files with the following parameters: time, easting, northing, elevation, intensity, classification, return number, scan angle rank. In order that radiometric

calibration of the intensity data could be attempted further ascii files were supplied on request. These included the automatic gain control values and post-processed navigation data with the timestamp and co-ordinates of the scanner origin.

The first pre-processing task for the ALS data was quality assessment. The data were converted to LAS format using LASTools (Isenburg 2011). The data were imported into OPALS (Technical University Vienna 2011) where the errors in elevation values at the flightline edge were quantified before adjustment using a Least Squares Matching (LSM) algorithm (Lichti and Skaloud 2010:121). The adjusted data was then cleaned by removing points with high eccentricity (defined as the distance from the grid point to centre of gravity of data points). The corrected overlapping flightlines for Area 2 were then combined to give a very dense point cloud (10 points per m²) using OPALS (*ibid*).

The data were then compared with a series of 350 ground control points (GCP) collected using the kinematic Global Positioning System (kGPS) (section 5.15) by calculating the root mean squared error (RMSE) in elevation (z). The elevation values of the data were then transformed in OPALS in order to reduce this error. The resulting point data was rasterised using nearest-neighbours in OPALS to give a DSM of cell size 1m. The point density per cell was calculated for Areas 1 and Area 2, both globally and for a number of sample areas that were selected to avoid the areas of strip edge overlap. Using these point density measures as a guide, the ALS data were then rasterised using moving planes interpolation to a final resolution of 0.5m for Area 1 and 0.25m for Area 2.

In order to provide input for further processing (specifically the LRM), the data was also filtered using OPALS to remove vegetation using the values of eccentricity and sigma (defined as the standard deviation of the elevation value, post interpolation adjustment) of each of the points. The optimal filtering of vegetation in this landscape was obtained through trial and error with a sigma value of <0.13 and eccentricity value of <0.8 being most representative of vegetation in the study area.

5.4 Ground Based Data Collection

Two sites within the Upavon area were selected for the collection of simultaneous ground observations to complement the ARS data.

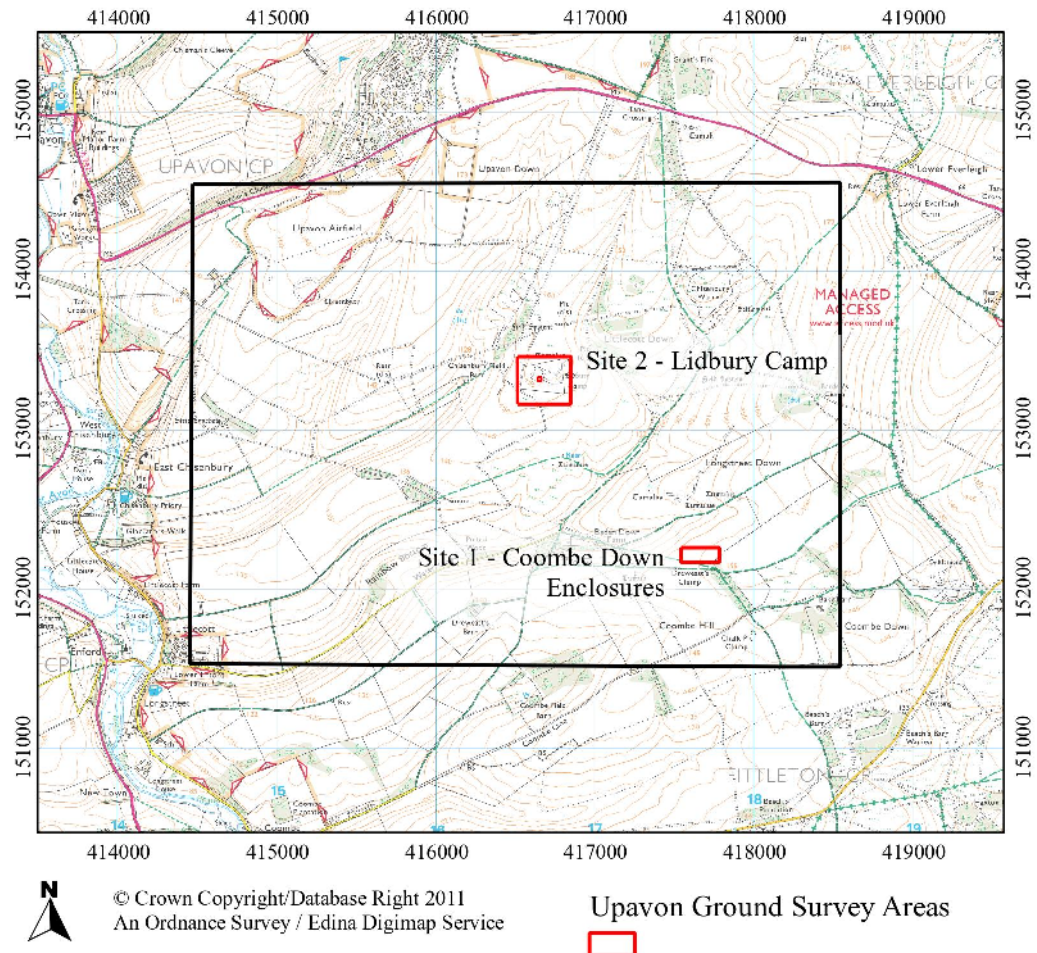


Figure 5.8: Upavon ground survey location map, Site 1 (Coombe Down Enclosures) and Site 2 (Lidbury Camp)

5.4.1 Upavon Field Site Site 1, Coombe Down Enclosures

Site one, Coombe Down Enclosures (SU 1767 5222), comprises a pair of Iron Age enclosures that were mapped from archive aerial photography as part of the NMP, when the site was still under cultivation (Figure 5.8). The site like much of the Plain is currently rough grassland that is occasionally grazed for scrub management. The two enclosures have been heavily ploughed and are barely visible on the ground (Figure 5.11).

This site was selected for the collection of soil moisture measurements and geophysical survey on the day of the bespoke airborne data acquisition (4th March 2010). A summary of the data collected is presented in table 5.6. A full geophysical report for the fluxgate gradiometry, earth

resistance and GPR surveys is contained in Appendix 2, including data collection, processing and interpretation.

Data Type	Area	Resolution	Date Collected
Fluxgate Gradiometry Survey	0.9ha (10 30mx30m grids)	Traverse 1m / sampling interval 0.125m	25/02/10
Earth Resistance Survey	30m x 15m	0.25m probe separation	04/03/10
	30m x 15m	0.5m probe separation	04/03/10
GPR survey	30m x 30m	Traverse 0.25m / sampling interval 0.05 / antennae 500 and 800mhz	04/03/10 30/10/10
Soil Moisture Samples	n/a	6 cores, 20cm depth	04/03/10

Table 5.6: Field survey data collected for the Upavon Site 1, Coombe Down Enclosures

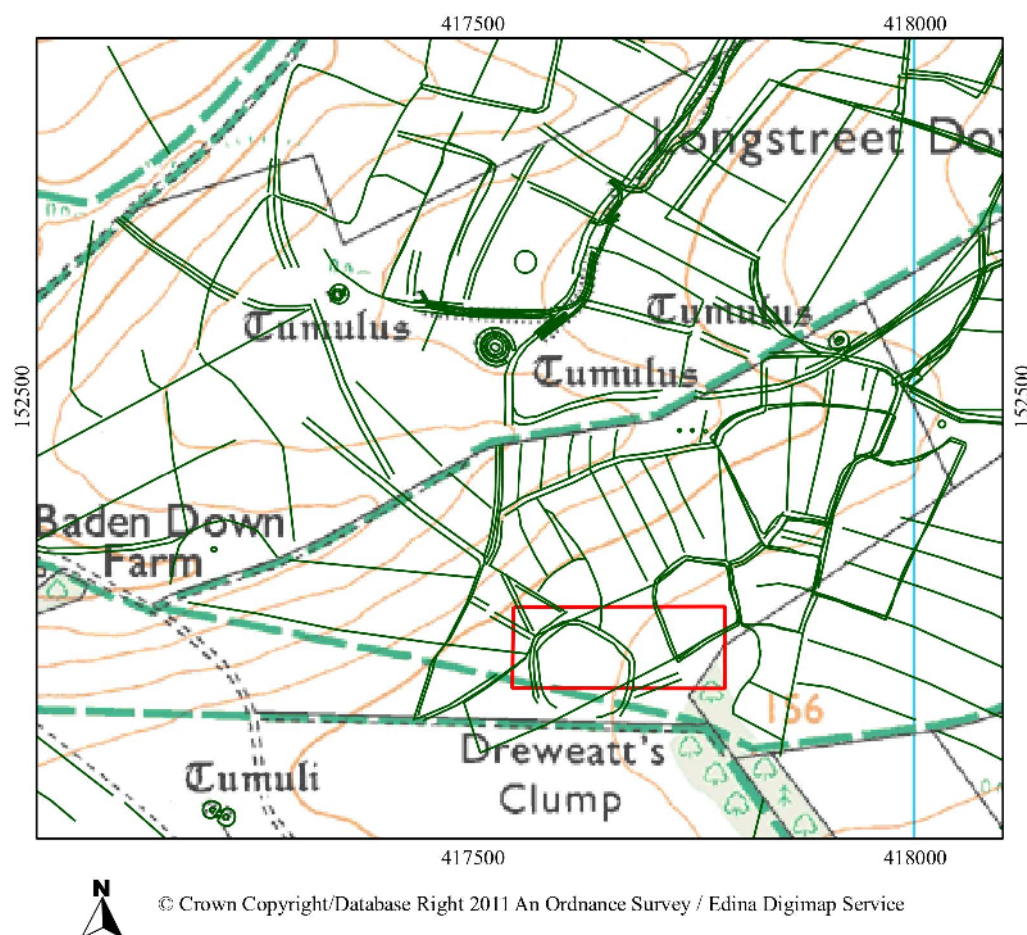


Figure 5.9: Upavon Field Site 1, Coombe Down Enclosures as recorded from the archive aerial photograph transcription (Wiltshire Historic Environment Record)



Figure 5.10: Geophysical survey of Upavon Field Site 1, Coombe Down Enclosures looking south-west, illustrating the lack of visible topography over the area of the enclosures

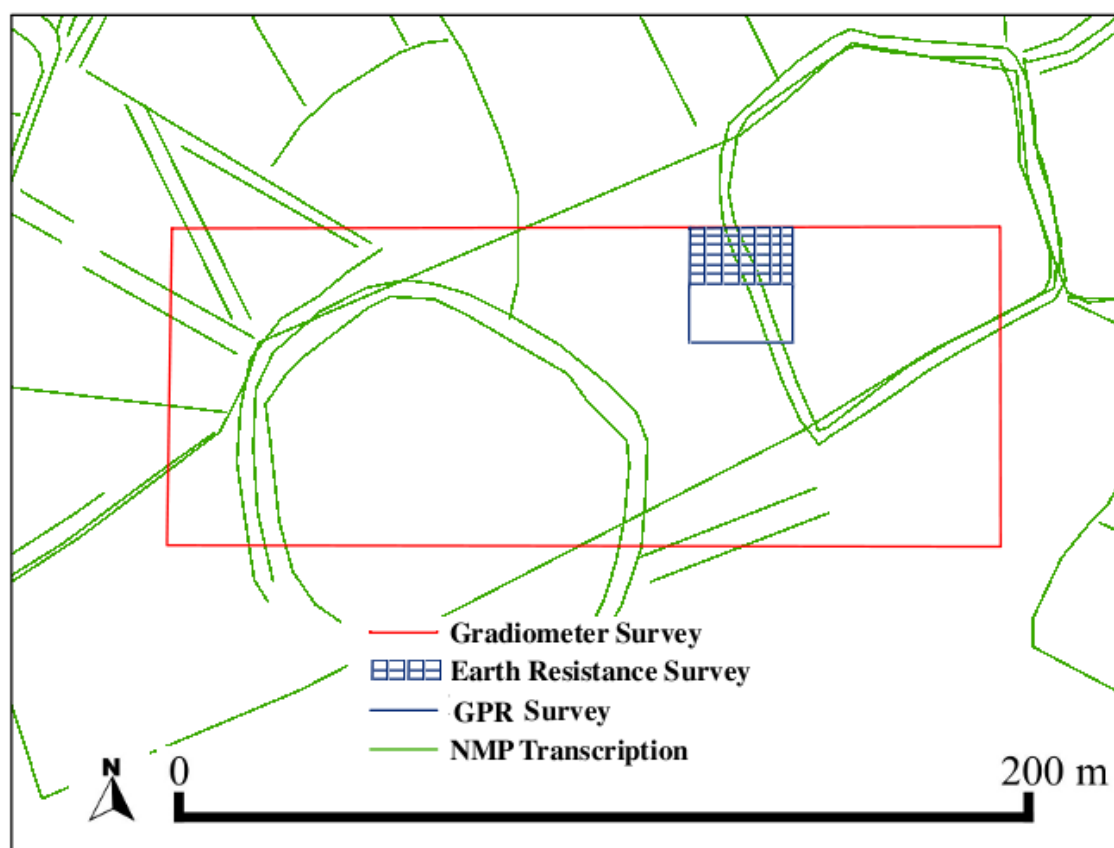


Figure 5.11: Location of geophysical survey at Upavon Field Site 1 (Centred SU 1767 5222)

Fluxgate Gradiometer Survey

A total area of 0.9ha of gradiometry survey was undertaken at Field Site 1 with a fluxgate gradiometer (Bartington Grad 601-2) prior to the airborne data acquisition to provide an accurate location and broad site context for the features selected for further survey (figures 5.10 and 5.9). The area was selected based on the HER transcription and grids were surveyed in using a Leica 1200 kGPS to ensure geospatial accuracy.

Earth Resistance Survey

Unlike the gradiometer survey, the results of the resistance survey are highly dependent on the ground moisture conditions (section 3.9.7). For this reason earth resistance data for site 1 were acquired in clear, dry conditions on the same day as the airborne data, 4th March 2010. A transect of 15m x 30m was recorded over a section of the bank of the eastern-most enclosure (figure 5.9) with the Geoscan RM15 resistance meter. The survey was designed to record the response from the top 0.25-0.5m of the soil column over the feature which would be most comparable to the data collected by the airborne sensor.

Ground Penetrating Radar (GPR) Survey

A 30m by 30m area of data was collected with a MALA Geosciences RAMAC X3M system, utilising a Mala shielded 800mhz antennae with attached survey wheel was used for distance measurement (figure 5.9). Like the earth resistance survey, the GPR survey was configured to maximise the data collected from the top 0.25m of the soil column.

5.4.2 Upavon Field Survey Site 2 - Lidbury Camp

Upavon Field Site 2 - Lidbury Camp (SU 1668 1533) is an Iron- Age rectilinear enclosure with very well preserved topography (figures 5.12-5.13). This area was selected for the collection of a detailed ground control point (GCP) profile using the Leica System 1200 kGPS to compare with the ALS - derived models. In addition a total of 320 ground control points were surveyed using kGPS across the whole of Upavon Area 1 to assist with georectifying the ALS data.

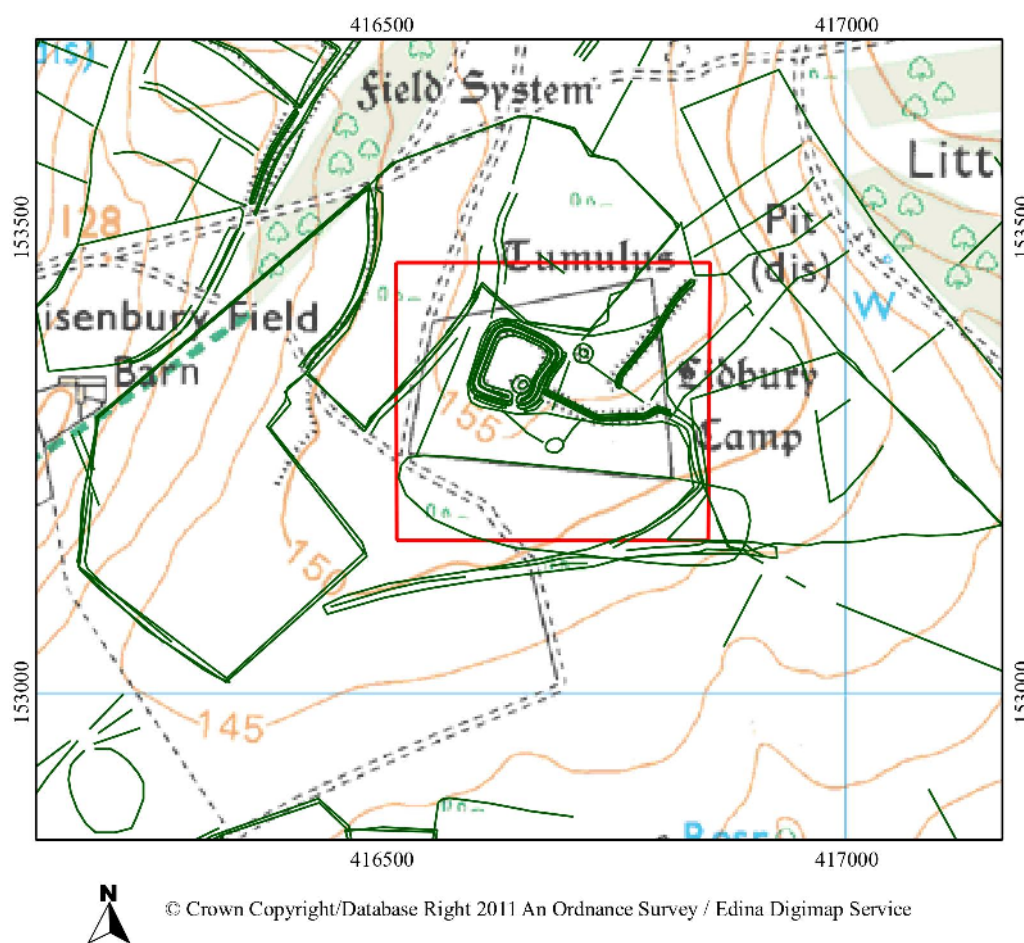


Figure 5.12: Upavon Field Site 2, Lidbury Camp as recorded on the Wiltshire HER



Figure 5.13: The prominent outer bank and ditch of Lidbury Camp (Upavon Field Site 2) looking south-east.

5.5 Summary

The rationale for the selection of study sites and availability of archive data made Salisbury Plain the clear choice for this research. The analysis of archive data was conducted for an area to the south of the village of Everleigh, while bespoke acquisition of hyperspectral and ALS data for the area south east of Upavon airfield in 2010 allowed for simultaneous ground survey data to be collected from field two sites. This chapter along with the preceding one, has provided an introduction to the location and archaeological importance of the study areas along with the general details of the data collected and any pre-processing. The details of the methods applied to these data in order to attain the objectives of the project are given in the Chapter 6.

6 Method

6.1 Introduction

This chapter describes the methods used to process the data collected for the Salisbury Plain Study areas of Everleigh and Upavon, (as detailed in Chapter 5) in order to achieve the project objectives laid out in Chapter 3. This research was designed to both fill the gaps in our understanding and trial innovative techniques for data visualisation and analysis. Building on previous research designs, this study attempts to overcome some of the issues with analysis of ARS that have been highlighted in the review of current literature (sections 2.3.2, 2.4.2, 2.5.2). Specifically attention has been paid to systematic quantitative assessment and comparison of archive data from different sensors for the same area with comparison to a baseline of known archaeological features derived from traditional survey techniques. With regard to the comparison of ground-based observations and ARS the primary aim was to reduce the uncertainty in previous studies introduced by the lack of contemporary data meaning that the effect of temporal changes on the data measured could not be quantified.

This chapter incorporates the processing workflow and *a priori* selection of software (section 6.2) along with the archaeological feature identification protocol laid out in advance of the ARS assessment (section 6.3). The next part of this chapter is devoted to the processing of the ARS data. Sections 6.5-6.8 cover the assessment of both archive and bespoke spectral data, while sections 6.9 and 6.10 detail the methods used to assess the airborne laser scanned data. Section 6.11 then details experimental techniques for combining data from multiple ARS sensors.

The latter part of the chapter focuses on the methods used to process and collate ancillary data in support of the ARS. This includes weather data (6.12), geophysical survey (6.13) and soil sampling (6.14), along with spectroradiometer measurements (6.15) and kGPS survey (6.16). Section 6.17 details how the ancillary data and ARS data were compared using statistical analysis.

The final section of this chapter details techniques for comparing the efficiency of multiple sensors for archaeological feature detection (6.18) by applying a range of statistical tests to the results of the analysis of archive data from the Everleigh Study Area. To aid the reader to identify sections relevant to each Objective of the research, a summary is included in table 6.1.

Objective	Sections
3	6.6, 6.18
4	6.5, 6.12
5	6.12, 6.13
6	6.7
7	6.6, 6.7, 6.8
8	6.7, 6.9
9	6.9, 6.10
10	6.9, 6.10
11	6.13, 6.17
12	6.11

Table 6.1: Summary of Objectives covered by each method section

6.2 Project Organisation

6.2.1 Workflow

The workflow for the project and data processing is shown in figure 6.1. The research was designed to allow a process of iterative feedback for the analysis of ARS data. As a consequence stages 1 to 3 were worked through twice. Initially the archive data for the Everleigh area were processed and analysed so that the results of this work fed into the specification for the bespoke ARS acquisition and experimental design of the contemporary fieldwork for the Upavon area. Once the newly acquired data had been processed through stages 1 to 3 the ancillary data could be incorporated (stage 4), culminating in the evaluation of the airborne datasets with respect to each other and contemporary ground observations (stage 5).

6.2.2 Selecting Software

Analysing remotely sensed data can be undertaken with a number of specialist software programs, both proprietary and open-source. Consequently the first task of the processing stages was to identify the most appropriate software. Early in the research it became clear that there was no perfect solution to the requirements of processing remote sensing data for archaeological purposes. Often the best solution was to combine software during the course of the processing to take advantage of each program's strengths and avoid their individual weaknesses.

The software used for each type of data is summarised in table 6.2 below. For each stage of the method the programs are cited in the relevant sections below, with full references to version and developer given in the bibliography.

Project Stage	Data	Task	Software Used
Everleigh	ALS	Processing & Visualisation	GRASS 6.4 / QGIS 1.7
	CASI Multispectral	Processing & Visualisation	GRASS 6.4 / QGIS 1.7
	HER Data	Processing & Visualisation	QGIS 1.7
	4-band AP	Processing & Visualisation	QGIS 1.7
Upavon	ALS	Pre-processing	LASTools / OPALS 1.0
		Processing & Visualisation	GRASS 6.4 / QGIS 1.7 / Fugro Viewer
	Eagle / Hawk Hyperspectral	Pre-processing	AZGCORR 4 / ENVI 4.7 / Opticks 4.6
		Processing & Visualisation	GRASS 6.4 / QGIS 1.7

Table 6.2: Summary of software selected for each stage

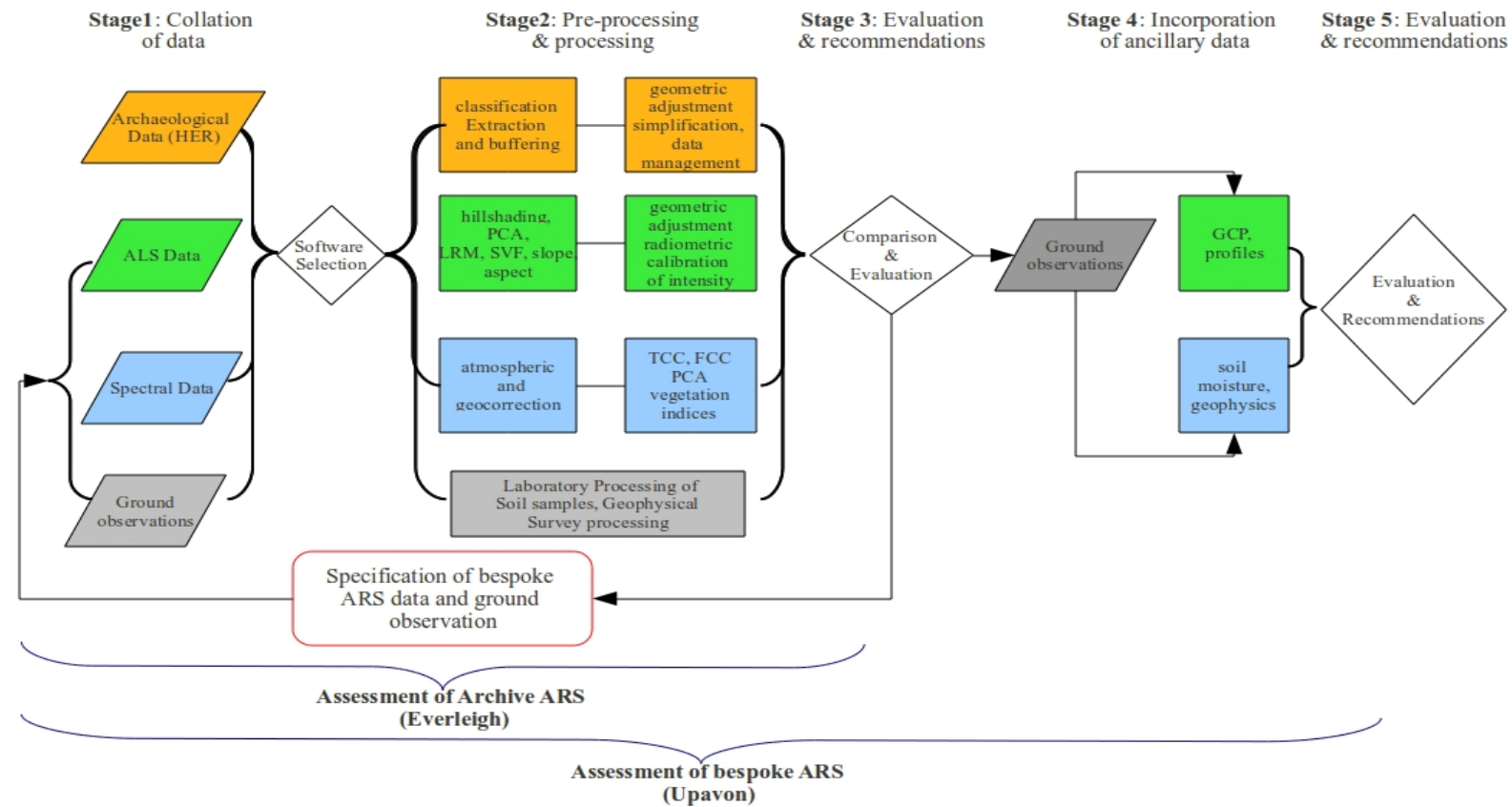


Figure 6.1: Flowchart illustrating the processing of airborne remotely sensed data and workflow for the study

6.3 Archaeological Feature Identification Protocol

6.3.1 *Archaeological Feature Identification Protocol (Everleigh)*

Archaeological entities in the landscape identifiable as such through their vegetation, soil or topographic properties, are referred to as “features” for the purposes of this study. In the first instance these are recognised simply as a change in contrast that identifies the archaeological feature from its surroundings. At this stage the morphology of the feature is recorded in the 'Type' attribute of the table along with details of it's appearance in the 'Description' field of the attribute table (6.3).

Interpretations of these features are based on their form and context as per aerial mapping guidelines laid out by the National Mapping Programme (English Heritage 2006) and are recorded in the 'Interpretation' field of the attribute table. In addition to this protocol, for the purposes of this project, each element of broader types such a barrow, were mapped as separate entities (e.g. mound and ditch) to enable a more detailed analysis. Additionally a single feature could be mapped in several parts only where a later development of the landscape, such as a trackway, clearly cuts what was once a single entity. Where there was uncertainty in this regard the feature was mapped with separate identifiers.

Despite recent guidance documents recognising the added value of the elevation data from ALS survey (Crutchley 2010), no protocol exists for integrating this into the traditional feature mapping processes that were devised for two-dimensional raster images. A number of methods were trialled as part of this project including 3D raster and point cloud visualisation, however for mapping purposes the best method of analysing the elevation was through drawing profiles (see section 6.9.7).

Features were initially recorded as shapefiles with the attributes shown in table 6.3 for each visualisation of the spectral and ALS data. For simplicity of format and cross-data comparability, features were mapped using polylines with the type of feature (linear, circular, area) denoted in the attribute table. This format was used for recording features identified in all the data sources. The 72 resulting attribute tables were collated in an MSAccess 2003 database for cross-data analysis.

Attribute	Shapefile Attribute	Description	Value Range	Thesauri / guidelines used
Unique Identifier	UID	Unique number ascribed to each feature for cross-data comparison	98-908	N/A
Type	Type	Basic morphology of feature digitised	A = Area L = Linear C = Circular Feature e.g. ring ditch	N/A
Description	Desc	Description of feature, typically including appearance, colour, clarity, relationship to other features	N/A	N/A
Interpretation	Interpreta	General interpretation	N/A	English Heritage Monuments Thesaurus
Land Use	Landuse		N/A	REP93 via INSCRIPTION
Comment	Comment	Any additional comments	N/A	N/A
Length	Length	Length of feature (to nearest metre)	Min length 14 Max length 843	Automatically calculated

Table 6.3: Attributes recorded for each feature in the Everleigh area

The attributes selected for recording at this stage reflected a compromise between speed of digitisation and detailed feature information and are typical of the standard short digital records collated by local historic environment records. UID allowed features to be compared across datasets; Type allowed for a description of the morphology of the feature (beyond the polyline representation); Description was used as a store for the visual description of the feature's appearance; Interpretation gave the archaeological feature type and was deliberately distinct from Description to allow for later reinterpretation if required; Landuse and Comments were used to categorise the current land use and make any notes on known former land use and Length was calculated automatically from the digitisation to enable comparison of percentage recovery of features. A scaled score for visibility, as used by Traviglia (2008), was considered but was not thought to represent the visibility of features better than the percentage length recorded and the descriptive notes. Percentage recovery of each feature was calculated after all visualisations had been assessed using the maximum recorded length for each feature from any visualisation. These figures were then used to calculate average percentage feature length recovery (APFL) for each visualisation by dividing the percentage recovery by the number of features recovered.

Initially all anthropogenic features were mapped from the data, including modern paths, military tracks and current field boundaries, to ensure rigour in the interpretation of the data. It was suspected in some cases that these features, particularly footpaths which were generally very sharply defined in the data (as often the thin top soil had been completely removed exposing the white chalk bedrock), were co-located with archaeological elements such as lynchets. In order to look at the patterns of archaeological feature recognition in this data, it was necessary to remove any purely modern elements from the final analysis. The decision on the origin of a feature was made using all the data sources, combining vegetation, soil and topographic factors and was confirmed with a field visit. Only features where modern origin could be stated with absolute certainty through map regression and site visits, were removed; all others were retained as archaeological features.

6.3.2 Archaeological Feature Identification Protocol (Upavon)

Due to the contemporaneous nature of the Upavon data, it was not necessary to record the features separately for each source of data. To streamline the process of assessment the HER data were recompiled into a single shapefile of all features, with the attributes shown in table 6.4. All features were checked for locational accuracy and consistency of type against the ALS model. For the stages of processing that required polygons (e.g. calculating the separation index, section 6.8.1), each polyline feature was buffered by 0.5m (based on the assessment of accuracy exercise described in section 6.10.2).

Attribute	Shapefile (Shortened Attribute)	Description	Value Range	Thesauri / guidelines used
Unique Identifier	UID	Unique number ascribed to each feature for cross-data comparison	98-908	N/A
Type	Type	Basic topography of feature digitised (as recorded from ALS data)	P – positive N – negative 0 – no topography	N/A
Length	Length	Length of feature (to nearest metre)	Min length 14 Max length 843	Automatically calculated
Topography Flag	ALS	Binary coded field showing whether the feature has extant topography	0 (no), 1(yes)	N/A
Location Correction Flag	Relocated	Binary coded field showing whether the feature's location was corrected using the ALS data	0 (no), 1(yes)	N/A

Table 6.4: Attributes recorded for each feature in the Upavon area



a) HER transcription from archive aerial photographs



b) Features plotted from the January CASI data



c) Features plotted from the May CASI data



d) Features recorded in the IFFR but not seen in either CASI dataset

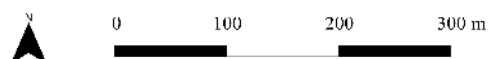


Figure 6.2: Examples of the feature mapping exercise undertaken in this study

Digital Spectral Data Processing

6.4 Introduction

This section covers the processing techniques applied to the archive and bespoke digital spectral data for the study areas. Initial assessment of land use (section 6.5) followed by the assessment of a number of visualisation techniques for the Everleigh data in order to compare visibility between them (Objective 8) and the processing of these models is detailed in sections 6.7.1-6.7.4. The focus of the analysis of the bespoke spectral data for the Upavon study area (section 6.8) was trialling automated methods of assessing spectral sensitivity (Objective 7).

6.5 Land Use Mapping

In order to contribute to current understanding of the impact of environmental and vegetation conditions (Objective 4), the archive CASI spectral data were used to create a land use map for the area using the True Colour Composites (henceforth TCC) of bands 7, 5 and 2 shown as red, green and blue respectively.

The TCC images were used to map land use categories over the study area as per the English Heritage REP 93 “land use” categories lists (Table 6.5). These terms are used by all local historic environment records and are based on unpublished wordlists in use in English Heritage and the RCHME prior to 1993, including broad grouping terms to allow recording at different levels of detail. Although some categories are more accurately defined as “land cover”, their use is standard and widespread in UK heritage datasets and as such were the most appropriate classifications to use for this study.

Polygons covering the Everleigh study area were mapped to a shapefile at 1:10000 scale, with the current land use and an additional comments field used to store notes about known previous land use in the area. Existing field boundaries and roads were used as delineations for the land use areas. The classification was verified and amended following field visits on the 22nd December 2009 and 18th October 2010. It was found that there was no land use change between the acquisition of the data and the date of the field visits.

Land Use Category	Parent Term	Scope Note
cultivated	cultivated	Nature of operations undetermined.
cultivation to a depth >0_25m	cultivated	Operations in excess of 25 centimetres.
minimal cultivation	cultivated	Land use involving no operations likely to be damaging to archaeological remains.
regularly improved grass	grassland heathland	Regularly cultivated and re-seeded grassland (but not including temporary grassland within arable rotation, for which use cultivated land)
disturbed grassland	grassland heathland	Areas of past and current land improvement, involving operations capable of disturbing the archaeology
undisturbed grassland	grassland heathland	If managed at all, then only to a low intensity, e.g. mowing, spraying etc. involving operations which are not archaeologically damaging.
scrub	woodland	The term includes invasive woodland characterised by the presence of birch, willow, alder, ash, sycamore, conifers as low trees with shrubs.
mixed woodland	woodland	In which coniferous and deciduous are present in roughly equal proportions.

Table 6.5: Land use categories used for the Everleigh study area

6.6 4- Band Vertical Aerial Photographs

The 4-band vertical aerial photography for the study area was supplied by the Ministry of Defence, and was available for two dates September 2006 and August 2007. These data were analysed in order to provide a comparative broad NIR (690-1000nm) sensor for the narrow band CASI spectral data (Objectives 3 and 7). Archaeological features were mapped following the protocol laid out in section 6.3.1 from true colour (red, green blue) and false colour (near infrared, green, blue) composites of the files. Due to the format of the supplied files it was not possible to view each channel of the images separately.

6.7 Archive Digital Spectral Data (Everleigh)

6.7.1 Single Band Mapping

The first mapping of archaeological features was from individual bands of the CASI flightlines in order to investigate variation in visibility across the electromagnetic spectrum and thus identify regions of spectral sensitivity (Objective 7). The bands were viewed in grayscale with a full histogram stretch and features were mapped at a scale of 1:4000 or less according to the protocol detailed in section 6.3.2. The flightlines were not mosaicked at this stage due to evidence of differential cropmark visibility when seen at different view angles in adjacent, overlapping flightlines (Lyall 2006). However no evidence of this discrepancy was seen during

the Everleigh data feature mapping exercise.

6.7.2 True and False Colour Composites

In order to evaluate 'standard' techniques (Objective 8), true colour composites were created from the CASI spectral imagery using bands 5 (671nm), 4 (550nm) and 2 (490nm) to approximate red green and blue wavelengths respectively and thus provide the closest image to standard photography, albeit at a significantly reduced spatial resolution⁸. In addition the features mapped from individual bands for the January and May data were analysed to provide data on the bands that would provide the optimal combination for false colour composites (figure 6.3).

As no standard for the creation of FCC images for archaeological interpretation was identified from the literature review, it was decided that the approach taken would be to use the bands that had provided the most unique features as these would indicate regions of the spectrum that were potentially more sensitive to archaeological feature visibility.

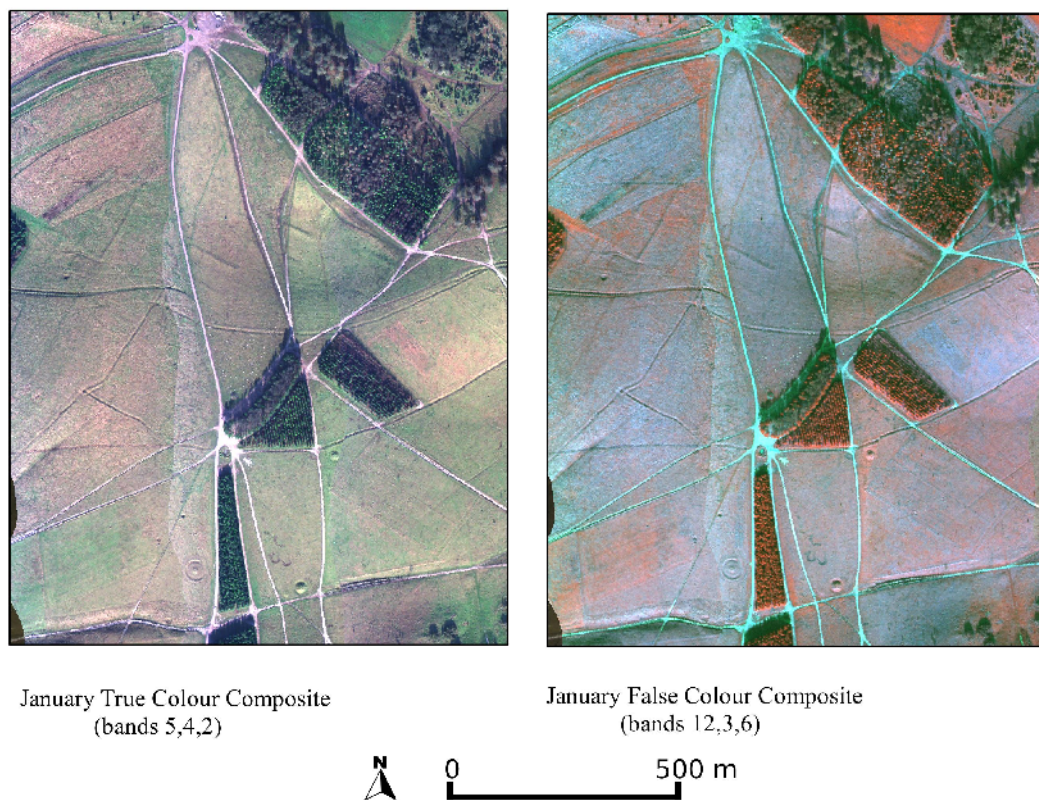


Figure 6.3: An example of true and false colour imagery in the Everleigh Study Area

⁸ Resolution of the CASI data was almost 8 times lower at 1.5m per pixel compared with the average resolution of an aerial photograph at 0.2m per pixel.

This approach based on visualisation is provided as a simplistic alternative to spectral clustering algorithms such as the Sheffield algorithm (Sanguinetti et al. 2005) or K-means, that require advanced statistical software such as R or Matlab which are not available to most historic environment researchers.

6.7.3 Vegetation Indices

The data were subjected to a range of common vegetation indices, carefully selected so that they had a substantial biophysical (as opposed to purely numerical) basis. This was crucial to the aim of identifying techniques from other disciplines (Objective 6) and also understanding the physical and biological parameters that influence the representation of archaeological features in spectral data (Objective 4).

A total of 12 indices were calculated using ENVI 4.7 (ITT Visual Information Solutions 2010) and are detailed in table 3.2 (figure 6.4). These indices cover the five categories of Broadband Greenness, Narrowband Greenness, Light Use Efficiency, Dry or Senescent Carbon and Leaf Pigments detailed in the technical literature review (section 3.10.3, table 3.2).

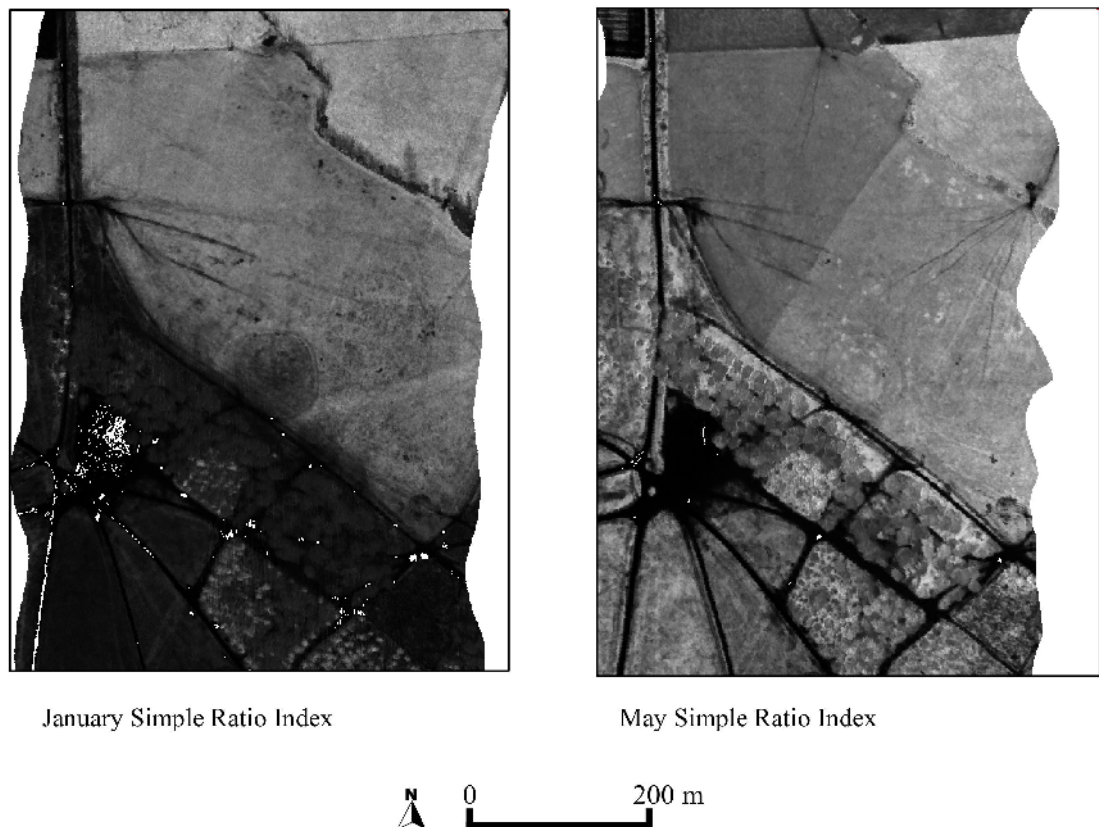


Figure 6.4: An example of the imagery produced by the application of vegetation indices in the Everleigh Study Area

6.7.4 *Principal Components Analysis (PCA)*

The multispectral data for the Everleigh area were transformed using PCA to examine the technique's efficiency and reliability compared with the single band analysis. PCA is the most commonly used method for spectral data reduction but it has never be compared quantitatively with other visualisations (section 3.10.5). Thus its inclusion in this study contributes towards Objectives 3 and 8.

A PCA transformation of all the bands was undertaken using the i.pca module in GRASS (GRASS Development Team 2010b). The bands used for the FCC composite (section 6.7.2) were also subjected to selective principal components analysis (sPCA) (after Traviglia 2008). This allowed the assessment of the effectiveness of PCA for visualising the regions of the electromagnetic spectrum that were pre-selected using other criteria (in this case feature uniqueness) to maximise feature detectability.

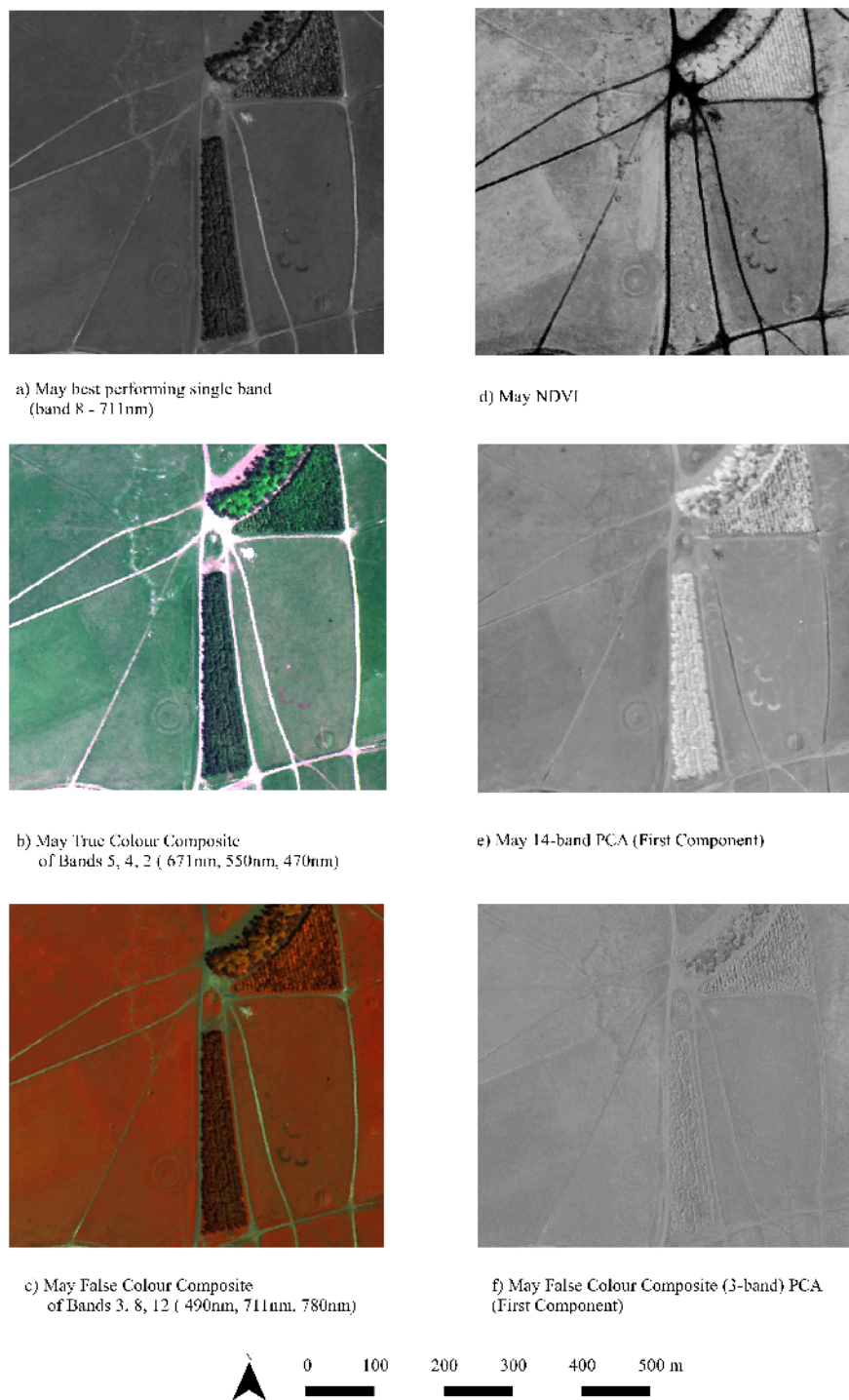


Figure 6.5: Examples of the processing techniques used for the archive spectral data in this study

6.8 Spectral Data Processing (Upavon)

The acquisition of Eagle and Hawk hyperspectral data for the Upavon area allowed an expansion of the visual quantification methods used for the archive data to incorporate digital assessment of spectral separability (Objective 7).

6.8.1 Archaeological Feature Separability

The concept of the Separability Index (SI), devised by Cavalli et al. (2009) was modified and applied to the spectral data using the spatial feature record from the Wiltshire HER as a baseline for analysis. Firstly the HER data were assessed with respect to the ALS data and contemporary vertical aerial photography in order to improve the quality of the baseline. Features were standardised and their visible extent mapped from the topographic data. Each feature was categorised as a positive or negative, reflecting its topography. Features that were not visible in the ALS data or aerial photography were classified as neutral and it was not possible to standardise their locations for this exercise. Each feature was buffered by 0.5m to reflect the spatial resolution and geometric accuracy of the spectral data (see section 6.10.1).

Masks were digitised for the spectral data to remove modern tracks and clumps of scrub vegetation leaving only areas of homogeneous chalk grassland. The 'background' spectral values were then assessed using the standard error to ensure homogeneity across the 1km² area. The area was divided into five sub-sets and histograms of each wavelength were compared with the histogram of the total background area, first by calculating the standard deviation from the mean then using the standard deviation / $\sqrt{\text{sample size}}$ (in this case 5) to calculate standard error. A series of 40 random linear features were also digitised across the background data to provide a non-archaeological control dataset for the SI calculation.

The original SI (Cavalli et al. 2009) was calculated using the following formula where D_{archa} is the integral of the histogram of the pixels representing archaeological features, D_{bck} is the integral of the histogram of the pixels representing only the background and $D_{\text{arch}}D_{\text{bck}}$ is the integral of the histogram of the pixels representing the whole scene.

$$S.I = \left(1 - \frac{\int D_{\text{archa}} D_{\text{bck}} dx}{\sqrt{\int D_{\text{archa}}^2 dx \int D_{\text{bck}}^2 dx}} \right) \times 100$$

During testing it was discovered that the original SI was sensitive to a number of factors. The first was the values of the DN which need to be in radiance and recorded as float data. The second was the ratio of background pixels to archaeological pixels in the scene. The impact of this ratio is not mentioned by Cavalli et al. presumably because the SI in the original study was

applied only to limited areas (single agricultural fields) where the ratio of background to archaeological pixels was close to 1:1. In upscaling the SI to encompass an entire landscape of homogeneous background there was a discrepancy in the ratio of background to archaeological pixels of an order of magnitude. This meant that the SI was not comparable between different sized groups of archaeological features and was also no longer in the 0-100 range. To solve this a weighting for the background to archaeological pixel ratio was included in the modified SI equation where PN_{total} is the number of pixels in the image and PN_{arch} is the number of pixels categorised as archaeological features. The resulting fraction was multiplied by 10 to bring the SI values back to the 0-100% range intended.

$$S.I_{area} = \left(1 - \frac{\int D_{archa} D_{bck} dx}{\sqrt{\int D_{archa}^2 dx \int D_{bck}^2 dx}} \right) \div \left(\frac{\sum PN_{total}}{\sum PN_{arch}} \times 10 \right) \times 100$$

The modified SI was used to calculate separability of three categories of archaeological features: positive, negative and neutral (no detectable topographic representation). The SI of the control sample of random linear features was also computed. The resulting SI values were compared between spectral bands and archaeological categories to assess sensitivity across the spectrum. Sensitivity of bands was recorded at the 90th percentile to identify the 25 best performing bands. Based on the analysis of the archive data, the percentile was not expected to be lower than this in order to observe the anticipated spread of sensitivity across the spectrum.

Airborne Laser Scanning

This section covers the processing techniques applied to the archive and ALS data for the study areas. A large number of visualisation techniques were assessed for the Everleigh data in order to compare visibility between them (Objective 8) and the processing of these models is detailed in section 6.9.

Section 6.8 looks at the techniques applied to the bespoke ALS data collected for the Upavon area including an assessment of the accuracy of buffering of polyline features (section 6.10.1) used to produce the spectral SI (section 6.8.1). Section 6.10.2 details the development of a method to assess the accuracy of ALS models compared with measured kGPS elevations for Upavon Field Site 2, Lidbury Camp (Objective 9).

The final section of the ALS methods covers the processing of the intensity data to improve its usefulness as a source for archaeological feature mapping (section 6.10.3) (Objective 10).

6.9 Archive Airborne Laser Scanning Data (Everleigh)

The archive ALS data were supplied in the form of eight space-delimited, last return, ascii files containing x,y,z and intensity values. The first task was to process these individual files into a single point dataset. After various software trials, the text files were imported into GRASS 6.4 (GRASS Development Team 2010b) as point data and aggregated to a single file and cropped to the area overlapping the spectral data to reduce processing time.

The topographic data were interpolated using a simple inverse distance weighted (IDW) nearest-neighbours method, most suitable for near continuous point data, producing a raster with 1m resolution. While this technique is not as accurate as some others (Mitasova et al. 2005), it provides a quick, mathematically simple and robust method for processing the large dataset. It is also the most commonly used method of interpolation, available in identical form across many software platforms, including ArcGIS and ENVI, and as such provides a baseline for comparison of other interpolation methods.

Until very recently, almost all analysis of ALS models was undertaken using one type of visualisation technique (shaded relief modelling). However there has been a recent upsurge in the number of visualisation methods published. To assess the suitability of these models to the study area the five most common (table 6.6) were applied to the IDW raster of the ALS data.

Technique	Acronym	Brief Description	Source
Shaded Relief Model	None used	Shaded relief modelling takes the elevation model and calculates shade from a given azimuth and altitude, thus highlighting topographic features	(Horn 1981)
Principal Component Analysis of Shaded Relief Models	PCA	PCA is a multivariate statistical technique used to reduce redundancy in multiple images. The product is a series of images representing statistical variance in the light levels of the original shaded relief images.	(Devereux et al. 2008)
Slope	None used	Slope mapping produces a raster that gives slope values for each pixel, stated in degrees of inclination from the horizontal.	(Jones 1998)
Aspect	None used	Aspect mapping produces a raster that indicates the direction that slopes are facing, represented by the number of degrees north of east.	(Skidmore 1989)
Curvature	None used	Profile curvature is a measure of the direction of steepest slope. The curvatures are expressed as 1/metres, e.g. a curvature of 0.05 corresponds to a radius of curvature of 20m. Convex form values are positive and concave form values are negative.	(Kennelly 2009)
Local Relief Modelling	LRM	LRM was developed for mountainous regions and produces a model where the affect of the macro-topography is reduced while retaining the integrity of the micro-topography.	(Hesse 2010)
Horizon Modelling	None used	Horizon Modelling is a visualisation technique based on diffuse light. The product is a representation of the total amount of light that each pixel is exposed to as the sun angle crosses the hemisphere above it. It synonymous with the Sky View Factor (Kokalj et al. 2011).	(Kokalj et al. 2011)

Table 6.6: The visualisation models applied to the Airborne Laser Scanned data

6.9.1 Shaded Relief Modelling

The first visualisations to be trialled were shaded relief models for Everleigh Areas A and B. The creation of shaded relief models was undertaken in GRASS 6.4 (GRASS Development Team 2010b) using the `r.shaded.relief` module. The impact of the angle of illumination above the horizon on feature detectability was assessed visually in 2° intervals in the range from 4°-25° reflecting the angles of raking light identified as ideal for microtopographic feature detection by Wilson (2000:46). The final shaded relief images were illuminated from an angle of 8° above the horizon which proved to be the optimum angle for highlighting archaeological

features in the gently rolling landscape of the Plain. The elevation data of the raster was exaggerated by a factor of five to improve the visibility of low-lying features. Shaded images were then created for angles at 45° intervals east of North, giving a total of eight images. Further subdivision of the angle intervals was not undertaken due to the large amount of redundancy in the data.

6.9.2 *PCA of Shaded Relief Images*

The PCA of the eight shaded relief images created (section 6.9.1) was created using the *i.pca* module in GRASS (GRASS Development Team 2010a). Features were mapped from each PC viewed as a grayscale raster to allow comparison of detectability between the components. The PC images were not digitally combined into a colour composite as this had been noted to obscure features in the analysis of the spectral data (section 6.4.5). The spatial records from all the PC images where features were detectable were also combined to create a single dataset for comparison with other techniques.

6.9.3 *Slope, Aspect and Curvature*

The next techniques to be trialled were slope, aspect and curvature mapping of the ALS DTM data. These models were calculated in GRASS 6.4 (GRASS Development Team 2010a) and specific descriptions are given in table 6.6. The creation of these visualisations requires no additional variables.

6.9.4 *Horizon or Sky View Mapping*

The technique of horizon or sky view mapping has been recently published (Kokalj et al. 2011) and is based on the method used to compute shadows for solar irradiation models. This calculation can be made using the GRASS module *r.horizon* (GRASS Development Team 2010b). This produces a model that reflects the total amount of light that each pixel is exposed to as the sun angle crosses the hemisphere above it; consequently positive features appear brighter and negative features are darker.

For the Everleigh study a number of horizon view models were created, with varying step sizes of 7m, 10 and 30m. The step size is a parameter of the algorithm that reflects the size of the smallest feature that could be mapped; 7m and 10m models reflect the expected size of the smallest archaeological feature that could be recognised in the landscape (and also the kernel size used for the local relief models, section 6.9.5), while the 30m model was selected for comparability with published examples. The model was calculated using intervals of 45° as with the shaded relief models (section 6.9.1).

6.9.5 Local Relief Modelling

The Local Relief Model (Hesse 2010) technique extracts microtopography from the DEM resulting in a image of positive and negative values similar to that of a gradiometer survey. The workflow implemented to create this model is detailed in table 6.7. The size of the kernal is chosen to reflect the expected size of the microtopography that is to be removed, in this instance kernal sizes of 7m, 9m and 30m were trialled.

The processing steps of the LRM are detailed in table 6.7. The first stage of the LRM was to use a kernal of variable size to smooth the DTM, removing the effect of micro topographic changes to create a DEM of the macro-topography. The original DEM was subtracted from this smoothed model, leaving a difference map which highlights variations in the surface that are not related to the macro-topography (figure 6.6). However at this stage the model was still biased towards small scale variation and there is some distortion of feature topography (Hesse 2010:68). Consequently a zero metre contour line was calculated from the difference map created in stage 3 of the process, and the elevations along this contour are extracted and interpolated into a new DEM which was completely purged of small-scale changes in topography. Finally this purged DEM was extracted from the original to leave the LRM of micro-topographic features which retain their original metric scale and proportions.

Although the Hesse's paper states that a number of software packages were combined to undertake the workflow, for the Everleigh project all the stages were computed using GRASS 6.4 (GRASS Development Team 2010a) using a custom script written for the task (see Appendix 1).

Stage	Description	Project Specific Information
1	create Digital Elevation Model (DEM) from the ALS point cloud	Base DEM interpolated using IDW, nominal resolution of 1m
2	Apply a low pass filter (LPF)	A 7x7m low pass filter was applied to the DEM (matrix as per Neteler et al. 2008:308)
3	Subtract LPF from original DEM	This creates a difference map which highlights local relief variations however it is biased towards small features
4	Extract the zero metre contour from the model created in Stage 3	To delineate positive and negative changes in local elevation
5	Extract elevations from the original DEM along the contour lines created in Stage 4 and interpolate a new DEM	DEM interpolated using IDW. This model will be purged of small-scale features
6	Subtract the purged DEM created in Stage 5 from the original DEM	This results in an enhanced local relief model which is less biased towards small scale features

Table 6.7: Workflow for the creation of a Local Relief Model, after Hesse 2010

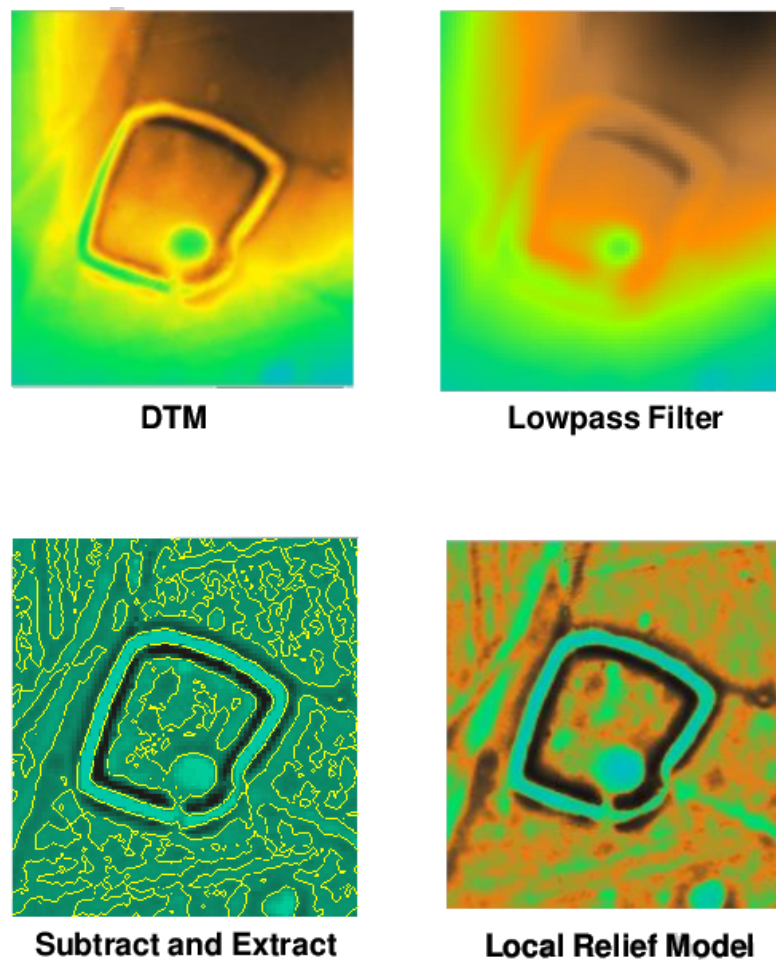


Figure 6.6: Simplification of the processing stages to create a Local Relief Model

6.9.6 Polynomial Texture Mapping (PTM)

Following a full review of the literature about PTM (section 2.9), it was decided that given the paucity of published technical data, the proprietary nature of the software required, and the lack of perceived benefit over other processing techniques, the technique was not suitable for application in this study.

6.9.7 Feature Mapping

The raster images created by all the modelling techniques detailed above were opened in QGIS 1.7 (Quantum GIS Development Team 2010) and archaeological features were mapped to a shapefile in an identical manner to those mapped from the multispectral data (described in table 6.3). In addition to the 2D display of the raster image, the features were cross-sectioned using the profile plugin in GRASS 6.4 (GRASS Development Team 2010b) allowing a description of their form as well as their plan and significantly aiding feature type interpretations (Figure 6.7).

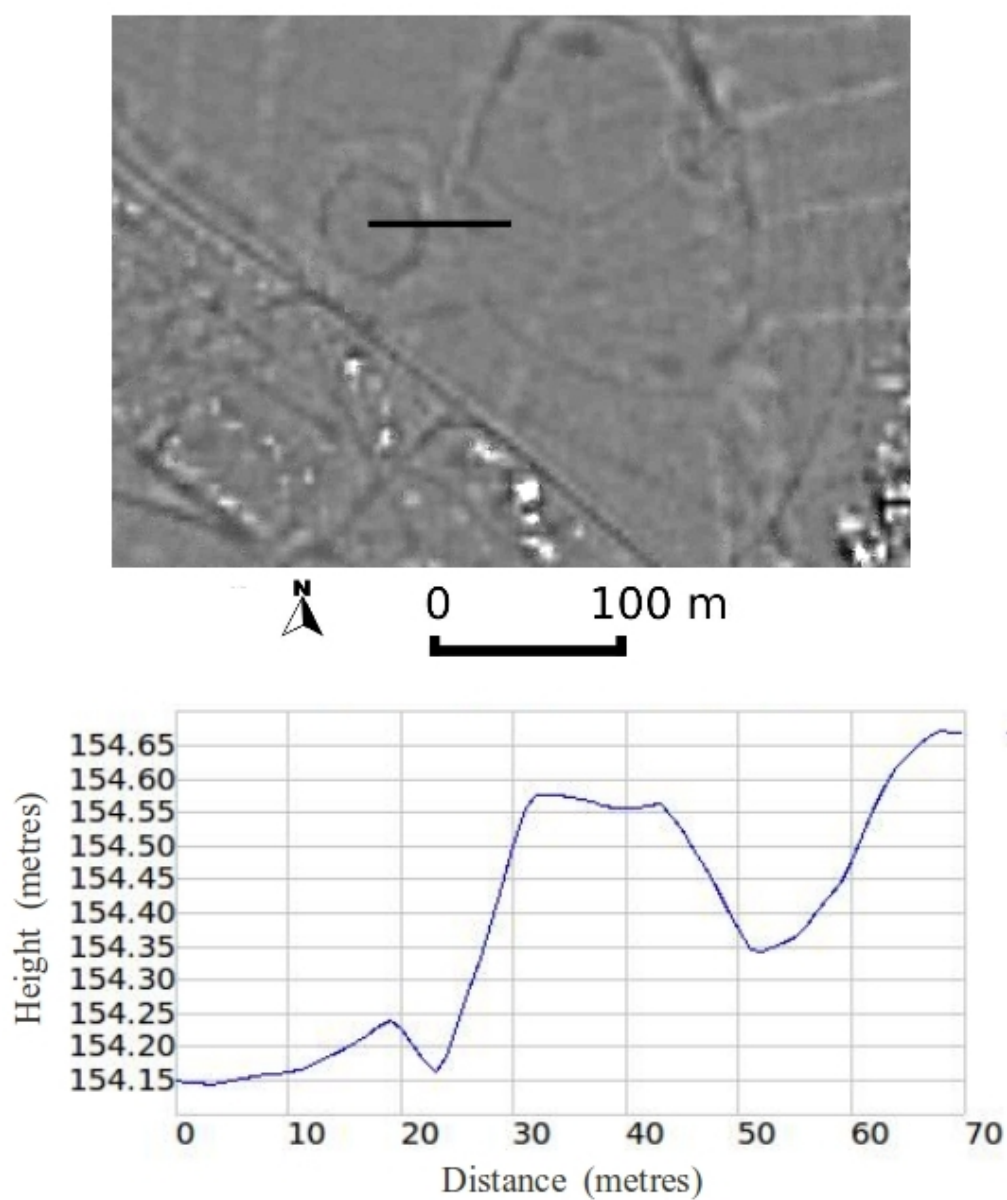


Figure 6.7: Profile of ground surface at the henge monument (SU 20645 52594 to SU 20716 52594). Location illustrated (top) and plotted (bottom)

6.10 Planned Airborne Laser Scanned Data (Upavon)

The planned ALS data provided the opportunity to address a number of objectives of the research. The principle benefit was in the collection of contemporary kGPS survey to allow a rigorous assessment of the accuracy of the LRM model (Objectives 8 and 9). The data also allowed for exploration of the links between ALS elevation and intensity data, hyperspectral data and soil moisture measures, contributing to Objectives 10 and 11.

6.10.1 *Assessing the Accuracy of the Archaeological Feature Buffering*

The ALS LRM 9m visualisation was used to assess the accuracy of a range of buffers that were required to be applied to the vectors representing archaeological features for some of the spatial processing such as the SI calculation (Section 6.3.2). Buffers of 2m, 1m and 0.5m were assessed by feature type (positive and negative) to see how representative the pixel values were of the category assigned to them. Histograms were computed showing the separability of positive and negative features for each buffer.

6.10.2 *Assessing the Accuracy of the LRM Model*

For Upavon it was also possible to assess the accuracy of the LRM model compared with the original DEM and a GPS transect across Lidbury Camp, an enclosure of Iron-Age date. The transect crossed the ramparts of the rectilinear enclosure as shown in figure 6.8. To assess the accuracy with which the LRM portrayed the microtopography of the enclosure, the angle of slope of the banks and ditches was calculated and the RMSE between the visualisation methods the original DEM and the GPS measurements was computed. Change in slope was used as the comparative measure rather than elevation change as the visualisations vary in scale and values. Contrary to elevation, the trigonometric calculation of slope also incorporates change in two dimensions of the profile, x and z (the third dimension y is held constant by the single direction profile). The RMSE in slope angle between the models and the measured values therefore provides a measure of the similarity of the shape of the features represented and thus the accuracy with which models such as the LRM represent real variations in elevation.

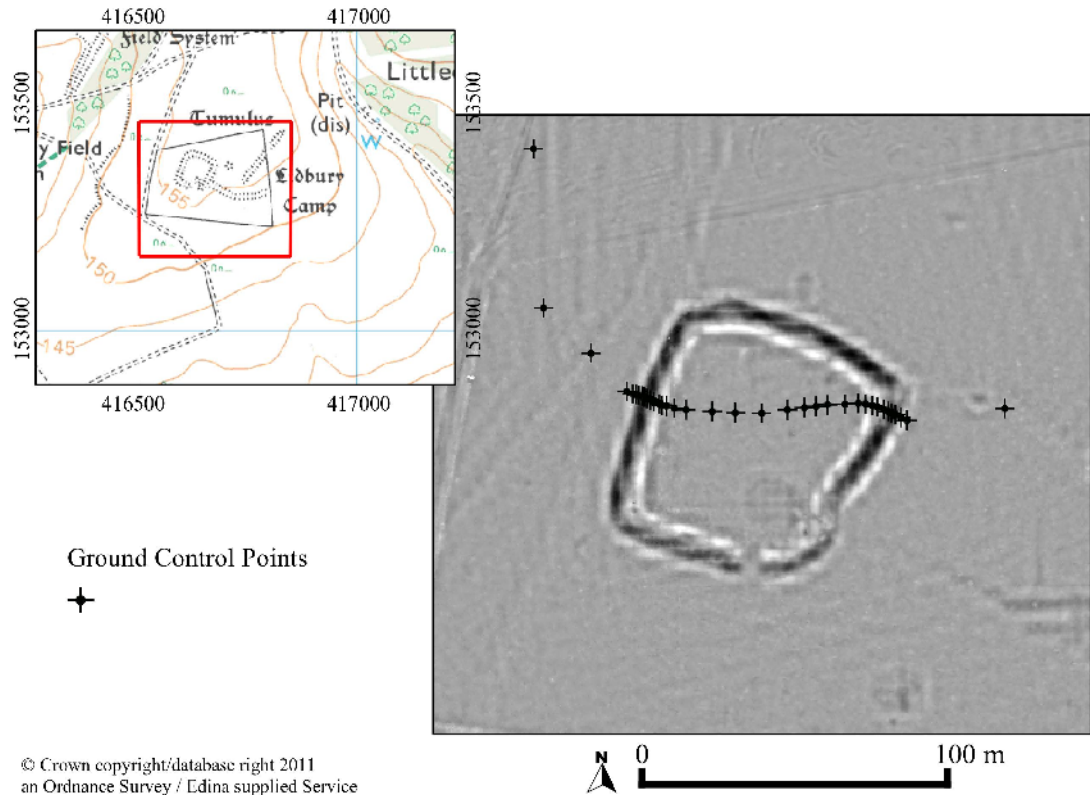


Figure 6.8: Location of the Ground Control Point profile over Lidbury Iron-Age Camp (shown overlaying the ALS LRM model)

6.10.3 ALS Intensity Data Processing

Following recent work in the field of improving the usefulness of ALS intensity data via calibration (section 3.9.4), it was intended to process ALS intensity data from Upavon in two ways. Firstly the intensity data were histogram matched in ENVI to the closest wavelength (1066nm, band 74) of the hyperspectral data. Secondly it was hoped that the OPALS software could be used to radiometrically calibrate the ALS intensity data. A technique for radiometric calibration of ALS data has been developed for Reigl sensors by Kaasalainen et al. (2009) and a sample of data from Upavon was transferred to Technical University of Vienna to experiment with the adaptation of the existing algorithm for the Lieca ALS50 sensor. Unfortunately it was not possible to produce a calibrated intensity image for a subset of the Upavon area within the timeframe of the project.

For comparison with band 74 of the hyperspectral data the intensity data were resampled using nearest-neighbours from 0.5m resolution to 1m resolution and the correlation between values for the same cell in both images was calculated (Section 6.17.1). The same procedures was used to compare the intensity measure to recorded soil moisture levels and geophysical survey (section 5.16).

Combining Data from Multiple Airborne Sensors

To access the full information content of the archive data, techniques for combining the spectral and topographic data were investigated using the archive data from the Everleigh study area (Objective 12). The contributing spectral and topographic source data was selected from the best performing methods identified in the individual data source analysis.

6.11 Digital Data Combination

6.11.1 Basic Raster Mathematics

The simplest technique for combining the data from two or more rasters is to add them together. Rasters created from the digital spectral data such as the FCC and PCA were simply added to the topographic data in the form of the original DEM or LRM using the raster calculator function in GRASS, having first ensured that the scales of the rasters were comparable. The DEM was scaled to match the spectral data by reducing the lowest values to 0m from 136.267m and multiplying all values by 292.137. The LRM was scaled by making all values positive by adding 1.891 and multiplying by 2962.838. These factors were calculated using the histograms of the spectral data for the study area to estimate the scaling required to match the raster data.

Initially the best performing individual band and the first PCA of the full spectral scene from the January and May flights were added separately to the scaled DEM. The same spectral data were then also added to the scaled 9m LRM.

6.11.2 Transformation Techniques

For the Everleigh data the Brovey transformation was selected as this is one of the simplest and most robust data integration techniques. The transform normalises up to three bands of multispectral data and multiplies the result by any other image (section 2.10.5). The Brovey transformation was trialled to improve the visibility from the January FCC, firstly using the original DEM then the 7m LRM and 10m Horizon model for the topographic layer. This was compared with the feature detectability results from the base FCC and ALS visualisation when assessed separately to discern whether the sharpening technique provided equal feature visibility. The formula for this was as follows where DN_{fused} is the transformed image produced from the input data in n spectral bands multiplied by the high resolution image $DN_{highres}$.

$$DN_{fused} = \frac{DN_{b1}}{DN_{b1} + DN_{b2} + DN_{bn}} DN_{highres}$$

Ancillary Data Processing

This section details the methods used to process all non-airborne data collected for the study. These data play an important role in achieving a number of objectives of the study. Archive weather data collected from the Met Office archive for each airborne spectral acquisition provided background information in support of the analysis of environmental conditions for Objectives 4 and 5 (section 6.12). The contemporary field surveys undertaken in support of the bespoke data acquisition by the ARSF (sections 6.13-6.14) provide information on the archaeological features and soil conditions using a range of geophysical techniques, and contribute to attaining Objectives 5 and 11. Sections 6.15- 6.16 detail the methods used to collect ground-based spectral and topographic measurements to improve the pre-processing of airborne data and provide comparative GCPs for assessing the accuracy of the ALS data (Objective 9).

The final section 6.17 details how the ground measurements were compared statistically with the airborne data using correlation analysis, allowing the quantification of the relationship between ARS and ground based observations (Objective 11).

6.12 Archive Weather Information

Supplementary weather data were collated to aid the interpretation of both the archive and bespoke digital spectral data with respect to broader environmental conditions (Objective 4). In the case of the archive data, the absence of ground observations means that weather data are the only opportunity to place the airborne data in context of soil moisture and atmospheric reflectance. For the Upavon data, the archive weather information broadens the context of the soil moisture and geophysical observations made on the day of the flights. This information combined with the quantitative assessment of feature detection will contribute to our understanding of the environmental conditions that effect the visibility of archaeological features within ARS.

6.12.1 Average Rainfall

Data were collated from the Met Office archive for the daily rainfall in the days leading up to the flight dates for the five weather stations closest to the study area (figure 6.9). As no data were available from Upavon airfield, the closest station was Collingborne Kingston at c.7km. The other stations selected; Larkhill, Boscombe Down, Tilshead and Alton Barnes all lay within 15km of the study areas.

Data was collected for the 14 days preceding the airborne data acquisition from each of the stations and then averaged. It is anticipated that due to the free-draining nature of the chalk bedrock and the shallow surface soils, the most significant rainfall measures will be those from the days immediately preceding the ARS acquisition date although it was not possible to find any research that detailed soil drainage patterns in this landscape.

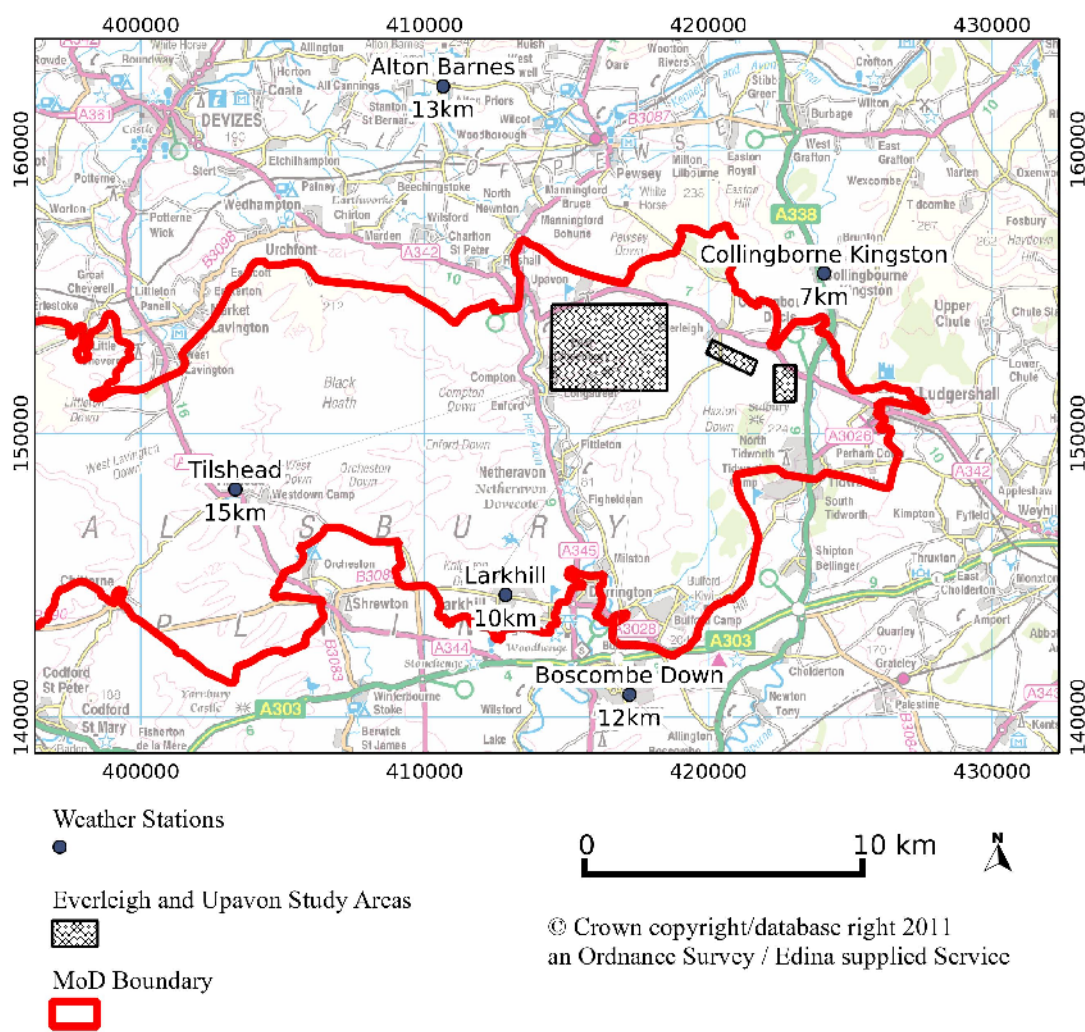


Figure 6.9: Location of weather stations with respect to the Salisbury Plain study areas

6.12.2 Soil Moisture Deficit

Soil Moisture Deficit, also known as soil moisture depletion is a measure of the amount of rain needed to return soil moisture content back to field capacity (the amount of water soil can hold against gravity (Penman 1948; Evans and Jones 1977)). As such it is a broad measure of the dryness of soil. Soil Moisture Deficit data were compiled from the Environment Agency Water Situation Reports for February – March 2010. No soil moisture deficit data were available for the period of the archive data (January and May 2001).

6.13 Geophysical Data (Upavon)

Upavon Field Site 1, Coombe Down Enclosures, was subject to geophysical survey before and during the airborne campaign. The full geophysical report for this site is given in Appendix 2; the details below represent the processing steps relating to the preparation of the geophysical data for integration with the airborne data.

Due to time constraints imposed by simultaneous data collection, the earth resistance and GPR survey were targeted over a single representative feature identified from the HER and confirmed by the fluxgate gradiometry survey; the bank of the eastern enclosure (SU 17712 52256).

All geophysical survey areas were laid out using the kGPS (section 6.16) to ensure high spatial accuracy. Survey data were georeferenced to the rinex corrected grid using a polynomial transformation in QGIS 1.7 (Quantum GIS Development Team 2010). The location of the surveys is given in figure 6.10.

6.13.1 Fluxgate Gradiometry Survey

In February 2010, gradiometry survey was undertaken at Upavon Field Site 1 with a fluxgate gradiometer (Bartington Grad 601-2) to provide an accurate location and broad site context for the bank feature selected for the earth resistance transect. The survey can provide a rapid overview of anthropogenic features in the subsoil providing a wider context and allowing the locations of the more detailed and compact earth resistance and GPS surveys to be determined. Although magnetic susceptibility cannot be detected by ALS or hyperspectral imaging, some of the features thus detected such as pits and ditches should also be detectable by the airborne sensors, providing an independent indication of the location and form of these features.

Survey was undertaken in a 'zig-zag' pattern with the direction of survey aligned north-south. A traverse interval of 1m and sampling interval of 0.125m provided a sound compromise between the detail of recording and speed of survey. Gradiometry survey is sensitive to magnetic changes caused by occupation and as such this technique was chosen to locate the bank and ditch features of the two enclosures at the site (figure 6.10). As the processing and interpretation of the gradiometer data are not key to the aims of this study they have been presented in a full geophysical report in Appendix 2.

6.13.2 Earth Resistance Survey

A transect of 15m x 15m of earth resistance data was collected over the bank of the eastern enclosure using a Geoscan RM15 resistance meter with MPX multiplexer and adjustable PA20 electrode frame in twin-probe configuration. Readings were collected in traverses of 0.5m width

with an interval of 0.5m, with probe spacings of 0.25m.

Due to the configuration of the probes these data were recorded as two interlocking surveys so these were merged and rescaled using Geoplot 3.0 (Geoscan Research 2004) from two 0.25 x 0.5m rasters into a single raster of 0.25m resolution. In order that the data could be compared quantitatively to the other airborne and ground based data, the resistance measurements were also converted to apparent resistivity using the formula below.

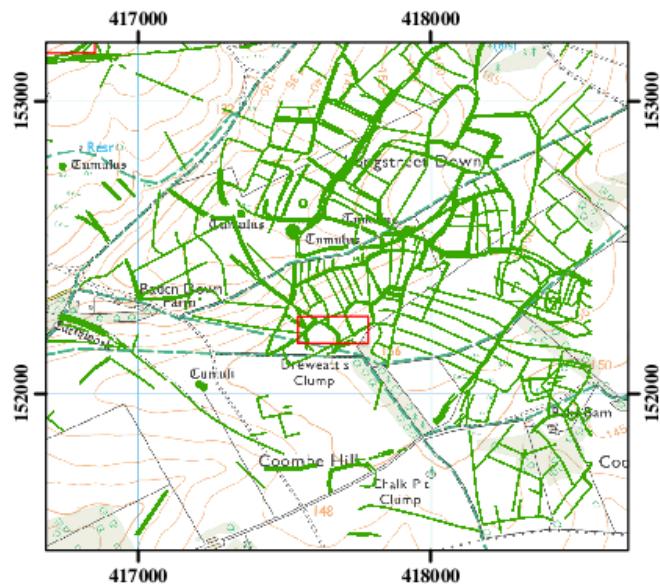
$$\text{apparent resistivity} = 3.1415 \times \text{resistance} \times \text{probe separation}$$

(ohm-metres) (Ohm) metres)

6.13.3 GPR Survey

As detailed in Appendix 2, the GPR survey was also undertaken on the day of the airborne data collection. The GPR data was expected to provide more detailed evidence for the sub surface structure of the features identified. The technique could therefore be used to complement and refine the data from the earth resistance survey.

An area of 30m x 30m targeting the bank of the eastern enclosure was collected with an Mala RAMAC GPR with an 800MHz antenna coinciding with the earth resistance survey. The data were collected along parallel W-E traverses 0.5m apart in a 'zig-zag' pattern. Traces were separated by 0.1m intervals. It was anticipated that the GPR survey would detect the horizon between the bedrock and the bank feature (to assess its depth below the surface) and that the signal of the bank material would be different to that of the surrounding soil matrix allowing its form to be visualised through the soil column.



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An Ordnance Survey Edina supplied service

- Gradiometer Survey
- ▢▢▢ Earth Resistance Survey
- GPR Survey
- NMP Transcription

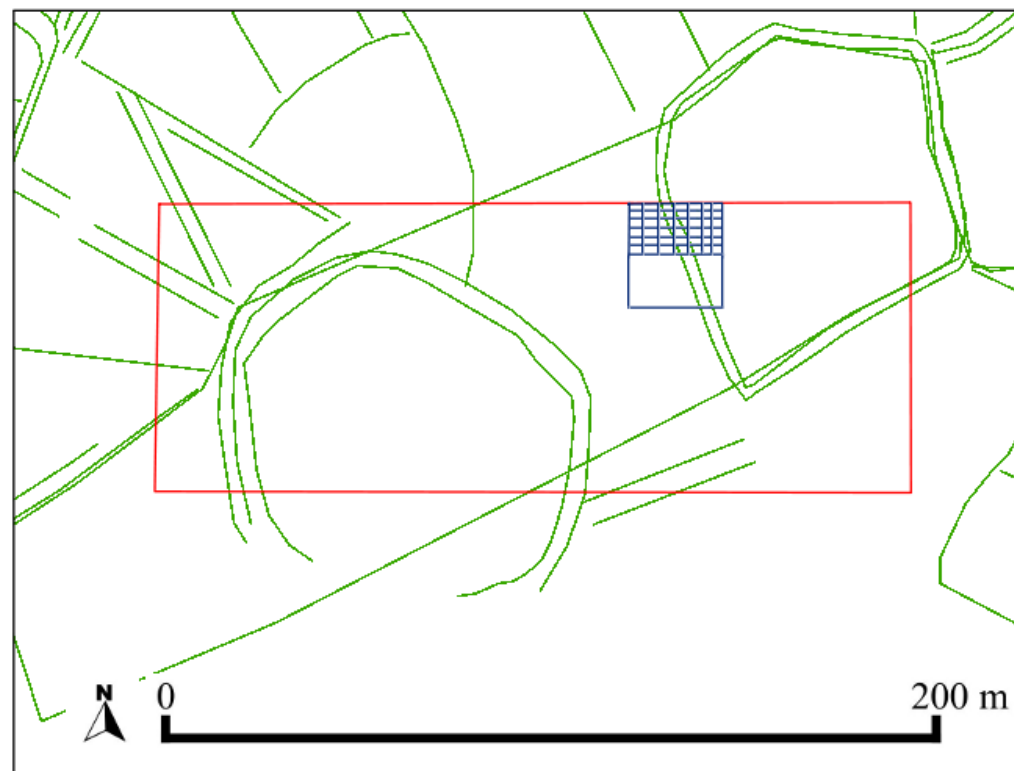


Figure 6.10: Location of the geophysical survey at Upavon Site 1, Coombe Down Enclosures, (overlain with the NMP transcription from the Wiltshire Historic Environment Record)

6.14 Soil Sampling

Soils in the area of the geophysical survey were sampled to assess local soil moisture levels (Objectives 4 and 11). It was originally intended that these should be compared to the global values provided by a series of permanent soil moisture probes positioned across Salisbury Plain for monitoring purposes by Cranfield University. However this supplementary information was not available due to the removal of the permanent probes at the end of January 2010 (Thomas Mayr 2009, pers comm)

6.14.1 Soil Sample Collection

A total of six auger cores were collected from the area of the earth resistance transect (figure 6.11). These were intended to be 30cm gauge auger cores designed to measure the differences in soil moisture within the topsoil at 10cm intervals, a total of 18 samples whose locations were recorded using the kGPS (section 6.16). In actuality the topsoil was so shallow in most cores it was only possible to measure the 20cm of soil before the bedrock layer and in two cores only 10cm of soil was retrieved.

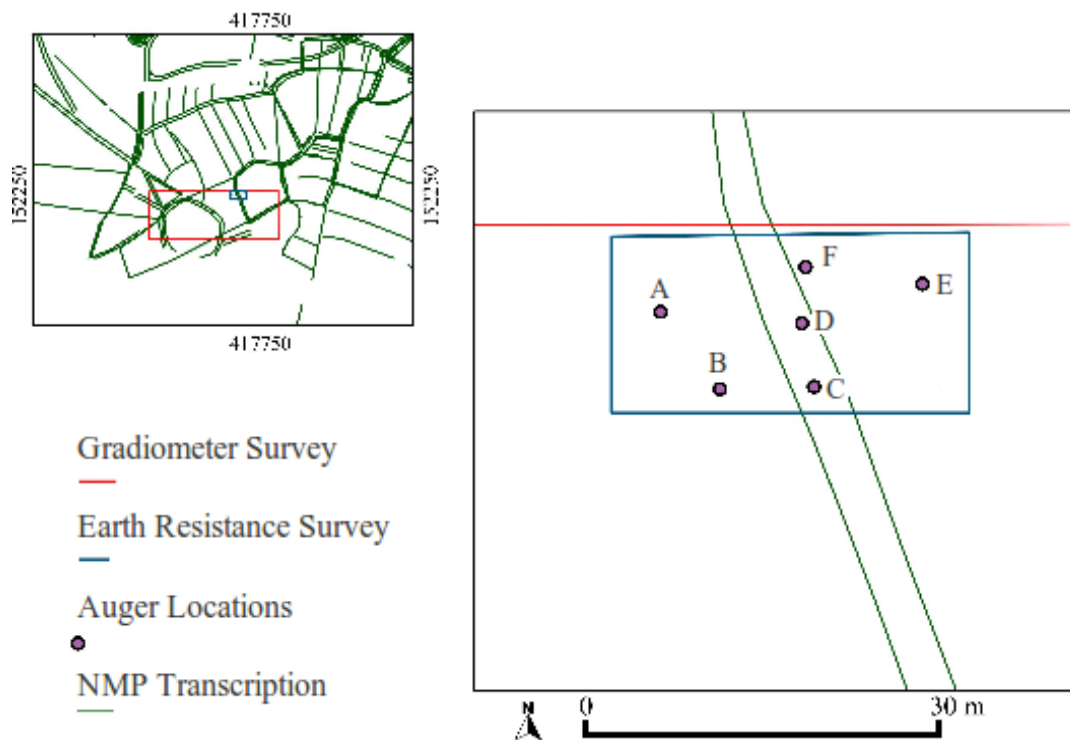


Figure 6.11: Location of auger survey, Upavon Field Site 1, Coombe Down Enclosures

6.14.2 Soil Sample Processing

The soils were processed to retrieve the moisture content as a percentage of dried weight. Each 10 cm sample was divided into three parts which were dried to a constant weight (as per Rowell 1994, Chapter 5). The moisture as a percentage of dried weight was then calculated and averaged for each sample.

6.15 Spectroradiometer Sampling

Forty-eight sample spectral profiles were collected during the two hour flight window (10.30-12.30) using the GER 3700, a high performance single-beam field spectroradiometer measuring over the visible to short-wave infrared wavelength range (350-2500nm) loaned from the NERC Field Spectroscopy Facility (FSF). The primary purpose of the measures was to enable localised atmospheric correction for the hyperspectral data for direct comparison with global techniques such as FLAASH. Three large tarpaulin targets were located to the south of site 1 at SU 174 520 to give black, white and grey spectra. Repeated spectral measurements of these targets were taken and post processed using the FSF post processing Excel templates.

The samples were calibrated using the FSF's post processing spreadsheet (NERC FSF 2010) and the regions of atmospheric absorption removed from the spectra. The spectra were then averaged for each target using SAMS (CSTARS, Univ.Calif, Davis 2005) and imported as a spectral library into ENVI.

Although almost 50 spectra were collected over the Upavon Field Site 1, most of the data were of poor quality due to a lack of metadata rendering many of them unusable for further analysis. In total, 10 spectra over the targets were used as a spectral library for visual comparison in ENVI but the numbers of spectra were not deemed sufficient to perform Empirical Line Correction of the airborne data.

6.16 Kinematic Global Positioning System (kGPS) Survey

To further aid the processing of the ALS data over 350 ground control points (GCP) were measured across the study area using the Leica 1200 series kGPS loaned from the NERC Geophysical Survey Facility (figure 6.12). The kGPS has a 3-dimensional accuracy of $<0.01\text{m}$. A point was measured from a stationary position at approximately 50m intervals along the survey track. Automatic collection of height data was simultaneously used to record points every 10m but comparison to the measured data showed that there was high average error to this data set and it was not used further.

A detailed transect of points was also recorded across the enclosure banks and ditches at Upavon Field Site 2, Lidbury Camp (SU16 63), to allow comparison of DEM accuracy over complex topography (figure 6.8, Objective 9). All GCP data were imported into Leica GeoOffice software (Leica Geosystems 2010) and corrected using the rinex data from five Ordnance Survey base stations in the locality (figure 6.13).

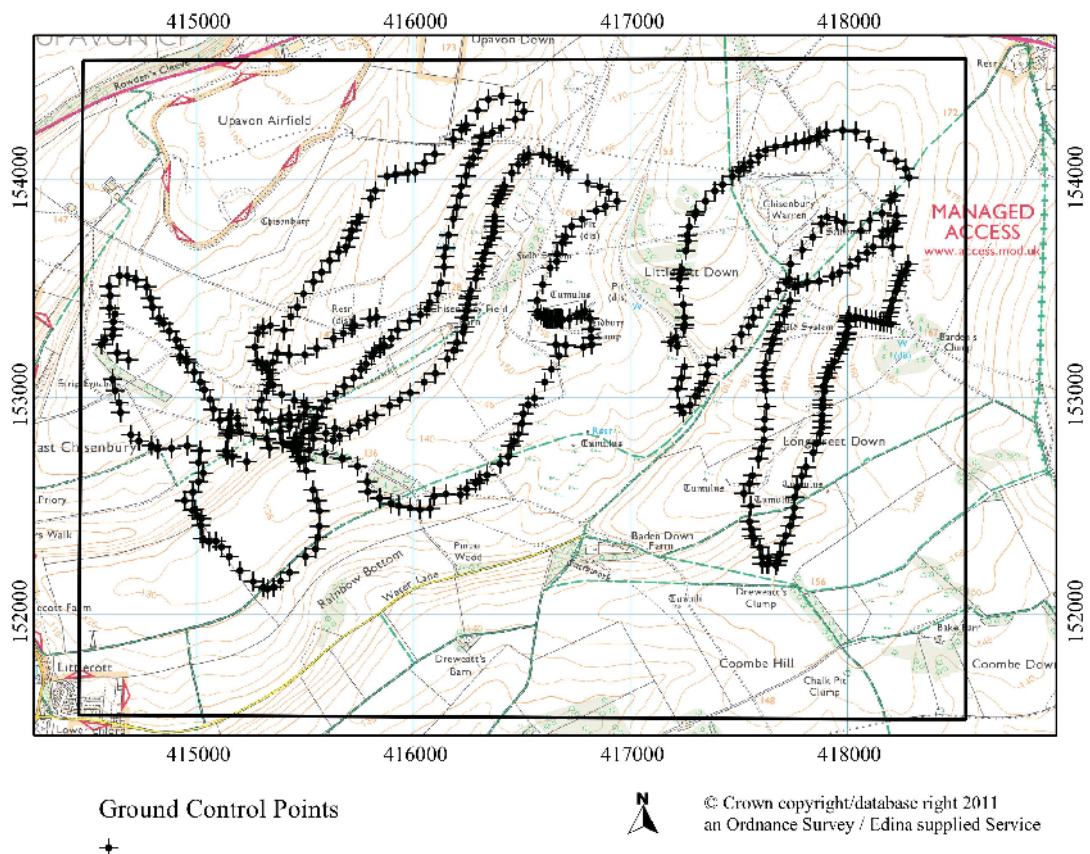


Figure 6.12: Location of the ground control points surveyed with kinematic Global Positioning System

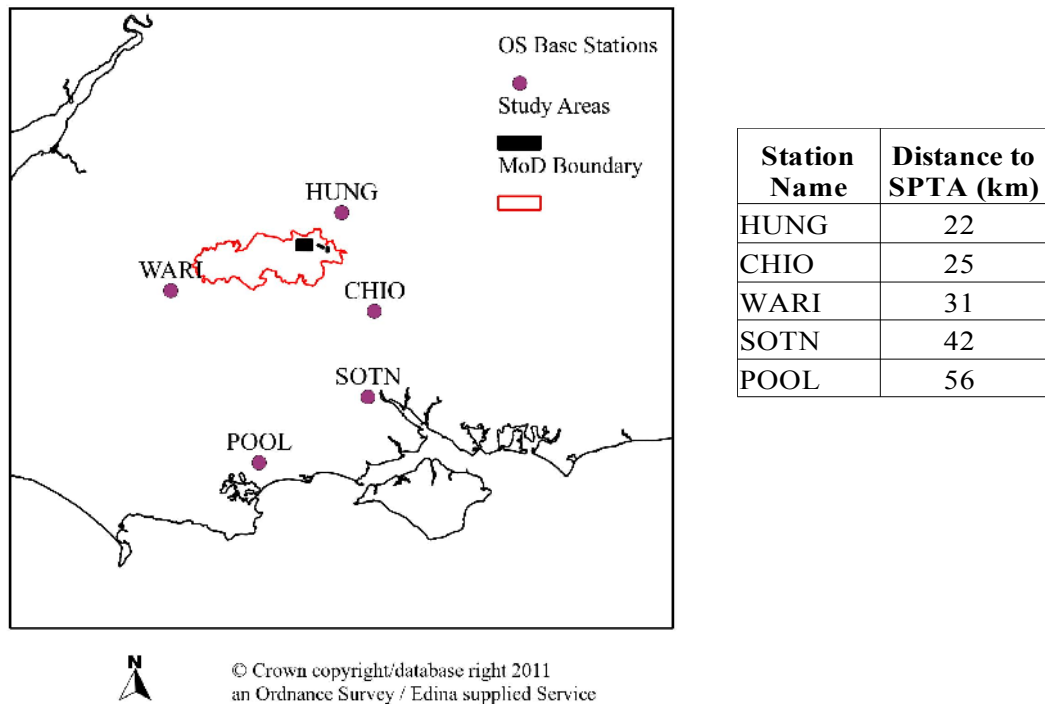


Figure 6.13: Location of the Ordnance Survey Base Stations used to correct the kinematic Global Positioning System survey data and their distances from the study site

6.17 Comparing Ground Based and Airborne Data

6.17.1 Correlation Analysis

For the Upavon study area it was decided that comparison between the ground based and airborne measures would be undertaken via statistical rather than visual analysis. The sample size for some of the data was small (just seven moisture measurements) and this must be considered when the results are analysed. However it was hoped that the assessment of statistical correlation between sensors would provide indicators of the relationships between key factors affecting the detectability of archaeological features. By comparing the relative impact of factors such as topography and soil moisture it should be possible to begin to draw out the complex multi-causality underlying detectability in spectral data.

The data selected for correlation analysis are listed in table 6.8. Initially all the datasets were analysed using the autocorrelation measure of Geary's M and Moran's C in ENVI 4.7 to assess the level of autocorrelation in each data set. Autocorrelation has a negative relationship to the value of the significance of the correlation coefficients between data types, with high autocorrelation leading to lower confidence in the results of the correlation calculation.

Category	Data	Details
Soil Moisture	% moisture content	measurements of % moisture in the top 0.1m of the soil profile
	resistance survey	apparent resistivity measured by probes at 0.25m separation
Topography	ALS DTM	0.25m resolution terrain model
	ALS LRM	0.5m local relief model
ALS Intensity	ALS Intensity	0.25m resolution intensity
	Spectral image 1066nm	1m resolution data used as the closest synonym to the ALS wavelength

Table 6.8: Datasets used for the correlation analysis

The assessment of correlation across the datasets detailed in table 6.8 was undertaken in two stages. Initially data for the area of earth resistance from Upavon Field Site 1 was analysed to compare the earth resistance and soil moisture measurements with the ARS data.

Drawing on the results of the initial correlation analysis, it was also decided to assess correlation in each band of the hyperspectral data against the percentage soil moisture measurements.

Comparing Across the Archive Airborne Data Sources

In order to assess the relative value of ARS data for archaeological prospection (Objective 3) it was necessary to derive methods for comparison of detectability across the data sets. This was undertaken using statistical analysis of visibility, in terms of both binary and Average Percentage Feature Length (APFL). Sections 6.18.1-6.18.3 detail the methods used for assessing binary visibility across the archive ARS data for the Everleigh Study Area, including an assessment of the impact of land use and feature type. The final section, 6.18.4, details how the APFL was compared.

6.18 Statistical Analysis

6.18.1 Binary Visibility

Once processed into shapefiles, the feature information from each of the data sources for the Everleigh study was compared using two approaches. The first was a simple binary approach to visibility, i.e. is the feature visible or not in a given source. Preparation of the feature data was undertaken in the MS Access database (section 5.3.1). The feature data for each of the ARS visualisations was imported into the program from the original shapefile and collated in a single table of feature lengths. These values were then coded to the values of 0 and 1 with 0 indicating no detection and 1 indicating partial or full detection. The extent of partial recovery of features was not analysed at this stage. Using the UID it was then possible to compare the occurrence of features across the remotely sensed data in cross comparison tables. It was also possible to quantify the number of unique features using this comparison technique. This table was then exported into SPSS 18 (PASW Statistics 2009) for all subsequent statistical analysis.

6.18.2 Comparing Land Use and Visibility

To determine the impact of land use on the visibility of features, the binary visibility data were also used to compare features across land use types (as defined in section 5.4) for each ARS visualisation. Each visualisation was assessed then assessed to see if land use was impacting on feature recovery rates in a significant way using chi-squared tests with the Cramer's V statistic indicating the strength of the relationship (or how likely it was to have occurred by chance) (Field 2009:695).

6.18.3 Comparing Feature Type and Visibility

The binary visibility was also analysed using the chi-squared test to identify significant differences in the recovery of feature types. The detailed feature types recorded during feature mapping were recategorised into three groups for this analysis depending on their topology as shown in Table 6.9.

Topographic Category	Original Feature Type
Positive	band, field boundary, lynchets, mound
Negative	Ditch, enclosure, hollow-way
Neutral	Vegetation feature, crop mark with no associated topography detected

Table 6.9: Simplification of feature type categories for chi-squared analysis

6.18.4 Comparing Percentage Visibility

In addition to binary visibility it was also necessary to quantify and compare the Average Percentage Feature Length (APFL) across the sources. The length of each feature in the shapefile was calculated automatically in QGIS 1.7 (section 5.3.1). The feature data for each of the ARS visualisations was then collated in a single table in MS Access and the maximum recorded length for each feature was calculated. The recorded length for each feature in each visualisation was then converted into a percentage recovery value using this maximum value. These values were then imported into SPSS18 as a single table of percentage recovery. Initially, the percentage visibility of features mapped from different sources was displayed as a boxplot to visually assess the differences between groups.

Different processing techniques using the same source data were treated as a single group and subjected to Friedman's ANOVA for non-parametric related samples (Field 2009:573). This test determines whether there is a significant difference between the sources in terms of percentage recovery and ranks them as to their efficiency. As a post hoc test, Wilcoxon paired analysis was undertaken to further interrogate the significant relationships identified by the Friedman's ANOVA. Wilcoxon's test shows the significance of the relationship between two sources and the directionality i.e. which of the two sources tested provides a significant increase in percentage feature recovery. This test was also used to compare the data across the groupings shown in Table 6.10.

Source	Technique
Archive Aerial Photography	Wiltshire HER data
January Spectral Data	Band 8
	PCA all bands
	FCC
	FCC PCA
	MRESRI
May Spectral Data	Band 8
	PCA all bands
	FCC
	FCC PCA
	MRESRI
ALS Data	Aspect
	Slope
	PCA
	Horizon Modelling (10m)
	LRM (9m)
Overlay	LRM / Jan PC1 overlay (addition)
	Brovey LRM / Jan FCC
	Brovey LRM / May FCC

Table 6.10: Table showing the groupings of data for Friedman's ANOVA

6.19 Summary

This chapter has presented the range of techniques used to process the archive and bespoke ARS and ancillary data for the Everleigh and Upavon study areas with respect to the objectives outlined in Chapter 3. The results of the processing are presented in the next two chapters.

7 Results - Individual Datasets

7.1 Introduction

The results of the study are presented in two chapters. This chapter reports the results of the analysis of the individual airborne remotely sensed and ancillary data for the Salisbury Plain study areas of Everleigh and Upavon. Chapter 8 presents the results of the integration of ARS and ground based data along with quantitative comparison of all ARS techniques for the Everleigh Study Area.

The results in this chapter are divided by data type, allowing comparative analysis between the two study areas throughout the section. As the approaches to the data for each part of the study differed, in each section techniques are divided by study area.

The study brings together a number of ARS datasets for each study area. For Everleigh this included two collections of CASI multispectral data, ALS data, modern military vertical aerial photography and archive vertical and oblique photography (summarised in the Wiltshire HER). For Upavon the HER record and planned ALS and hyperspectral data were supplemented by geophysical data and soil moisture measurements. The data collected are undoubtedly suitable for detailed analysis and comparison with regard to many archaeological research questions, however the results presented below focus tightly on achieving the technical objectives set out in Chapter 3.

Section 7.2 gives the results of the land use mapping for the Everleigh Study Area underpinning the analysis of the effect of land use on feature visibility in the ARS data (sections 7.4.3 and 7.6.9). Section 7.3 presents the results of the analysis of the MoD 4-band aerial photography. In section 7.4 results from both the archive multispectral data, including single band analysis, digital combination of spectral bands and the use of vegetation indices. The results from the archive spectral data are also analysed with respect to feature visibility and land use in section 7.4.3. In section 7.5 the results of the analysis of the planned hyperspectral data acquisition (Upavon) are detailed, focusing on the calculation of the separation index for individual bands and vegetation indices.

Sections 7.6 and 7.7 give the results of the analysis of the ALS data for both study areas, including the impact of modelling techniques on feature visibility. The archive ALS data results (Everleigh) are described in sections 7.6.1-7.6.8, while sections 7.7.1-7.7.4 cover the analysis of the planned ALS data (Upavon). As with the spectral data, the effect of land use on feature visibility for the ALS visualisations is explored separately in section 7.6.9.

Digital Spectral Data

As documented in section 4.4.7, the archive spectral data for the Everleigh Study Area was examined in two tranches. Firstly, a rapid assessment of land use for Areas A and B (figure 7.1) was undertaken (section 7.2) along with an assessment of the 4-band aerial photography (section 7.3). Single band and TCC / FCC mapping of the spectral data was also undertaken on Areas A and B. Based on the quantity of features identified in this analysis, it was necessary to define a geographically smaller subset (Area C, figure 7.1) upon which all further processing of the spectral data was performed (section 7.4). For consistency of comparison across visualisation techniques, all the archive spectral data results presented in this chapter are for Area C only. The comparison of archaeological feature detectability in Areas A and B compared with Area C is given in the next chapter (Section 8.9).

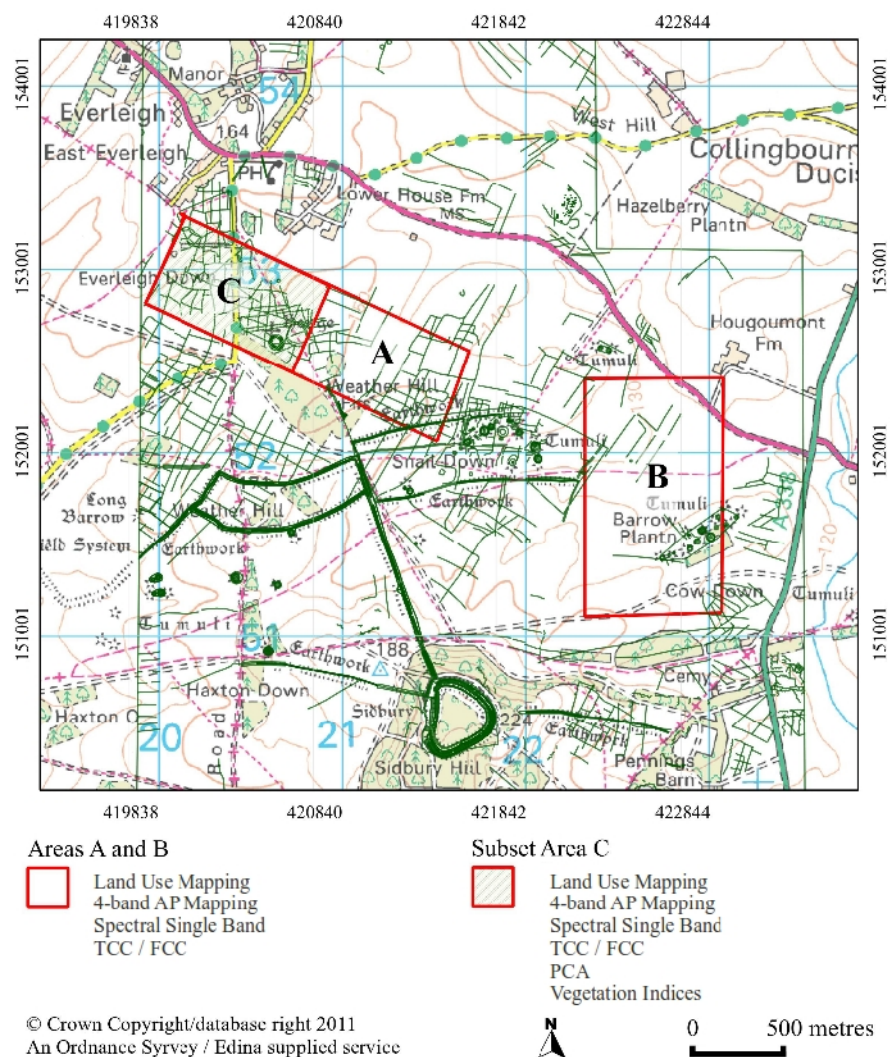


Figure 7.1: Detail of spectral processing undertaken for each of the Everleigh Study Areas

7.2 Land Use Mapping

The results of the land use mapping exercise for the Everleigh Area were appended to each archaeological feature to allow analysis of the impact of land use on visibility (sections 7.4.3 and 7.6.9) following the method outlined in section 6.5 and are presented in figure 7.2. The analysis showed that the majority of the area analysed was classified as disturbed grassland (63-65%) (figure 7.3).

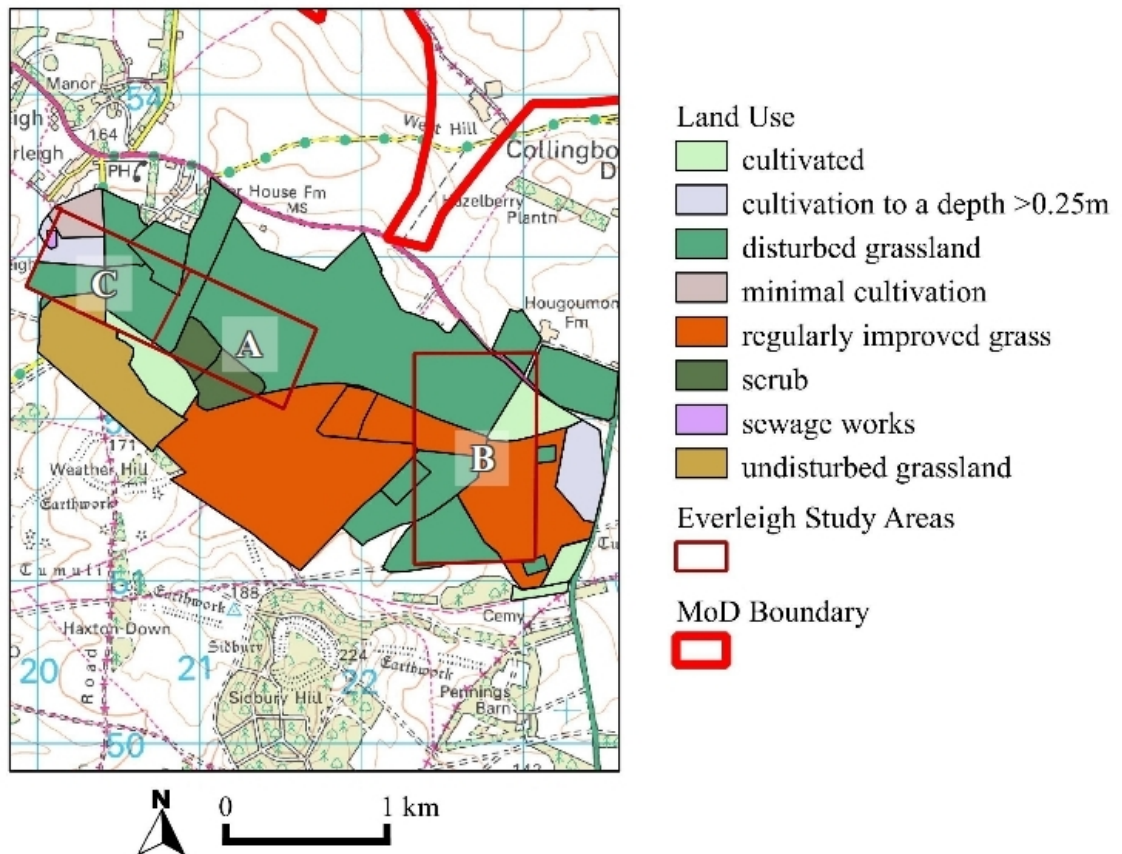


Figure 7.2: Land use mapping for the Everleigh Areas A, B and C (see section 6.5 for class definition)

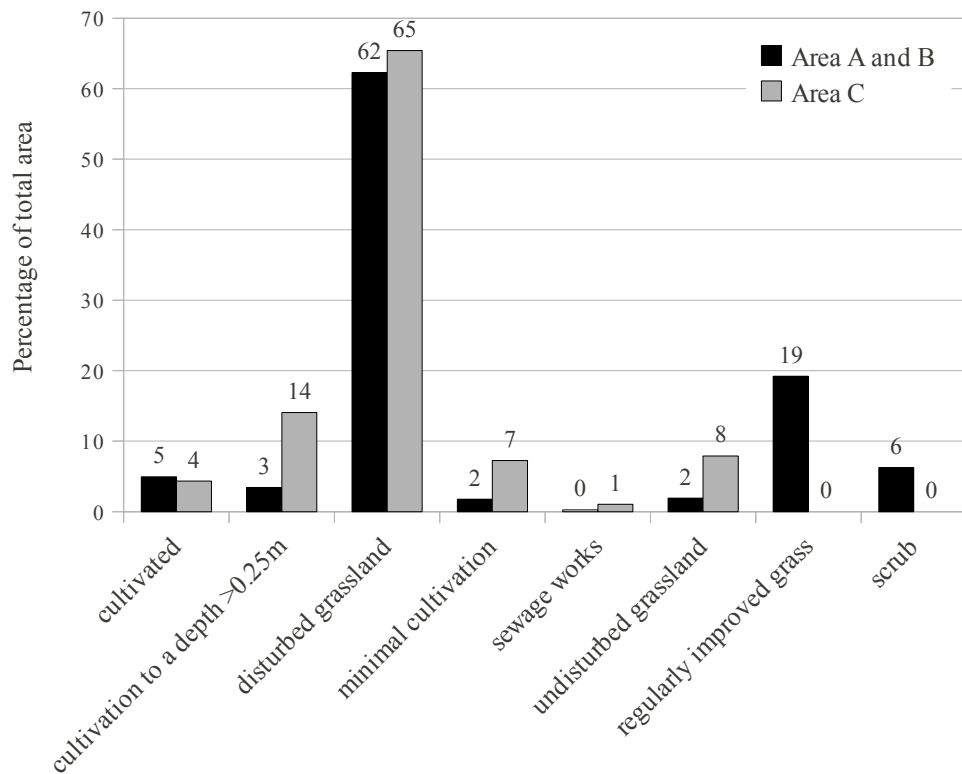


Figure 7.3: Percentage land use categories, Everleigh Study Areas A and B

7.3 4-Band Aerial Photography (Everleigh)

The results from the 4-band aerial photography analysis for Areas A and B are presented in table 7.1 below. Very little difference was seen between the TCC and FCC imagery and no unique features were recorded from the vertical photography when compared with the other ARS data, and only a small number that had not previously been recorded were visible. In general however, few features were visible in these images with no more than 20% of the 290 features identified in this area detected using the 4-band aerial photography (see section 7.5 for full comparison to other ARS data sources).

Date of Acquisition	Composite	Number of features recorded (n=290)	Number of HER features recorded (n=151)	Number of features not recorded in the HER
September 2006	FCC	52	27	10
	TCC	54	26	8
August 2007	FCC	45	22	8
	TCC	42	22	8

Table 7.1: Table showing relative feature recovery rates from the 4-band vertical aerial photography (total features numbers in brackets)

7.4 Archive Spectral Data (Everleigh)

7.4.1 Introduction

The careful selection of the Everleigh case study meant that a number of research objectives could be met with these data. The availability of complementary data in the form of other archive ARS sources and the existence of full NMP mapping for the area contributed to Objectives 3 and 5. Additionally, due to the repeated acquisition of spectral data in the same year it was possible to assess the impact of environmental conditions on feature visibility (Objective 4). Although the archive spectral data was limited to visible and NIR wavelengths (450-891nm) there was also opportunity to examine spectral sensitivity (Objective 7). All results below are for Everleigh Area C only (figure 7.1).

The spectral data from both acquisitions performed well in comparison to the baseline number of features given by the Wiltshire HER. Often poor spatial resolution when compared with aerial photography is cited as an inhibiting factor for historic environment professionals considering using this type of sensor (Beck 2011), however the results of the feature mapping exercise (sections 7.4.2-7.4.7) show that despite this, the individual spectral dataset still showed between 41% and 48% of all known features (table 7.2). To better understand why and how features are represented in the data, the results have been interrogated with a specific focus on assessing archaeological feature type, environmental factors and cross-data comparability.

7.4.2 Single Band Mapping

The first stage of analysis undertaken on the spectral data was a band by band visual interpretation of feature visibility, the results of which underlay all subsequent use of the archive spectral data. Table 7.2 shows the results of the single band mapping exercise in detail and it can be seen that each data collection individually returned less than 50% of known archaeological features in the area. However the complementarity of the data was such that when the information from the two flights was combined, the number of features mapped rose to almost 65% of the total known from all the sources used in this study. The complementarity of multiple acquisitions was also illustrated by the fact that only 41 features (24%) were identified in the spectral data from both flights.

The analysis of the spectral datasets shows that there was a 7% difference in the number of features visible between the January and May datasets. This difference in detection was also reflected in the average percentage length (APFL) of features recorded which was 61.2% in

January and 56.8% in May. This measure was used to indicate proportional, rather than binary recovery of features (as detailed in section 6.3.1).

Month of Flight	Number of Features Mapped	Percentage of Total Number of Features	Number of Features Unique to Month (not mapped in other spectral data)
January	82	48%	37
May	69	41%	34
January and May Total	110	65%	
Both January and May	41	24%	

Table 7.2: Relative feature recovery rates from the archive spectral data (January and May 2001), Everleigh Area C

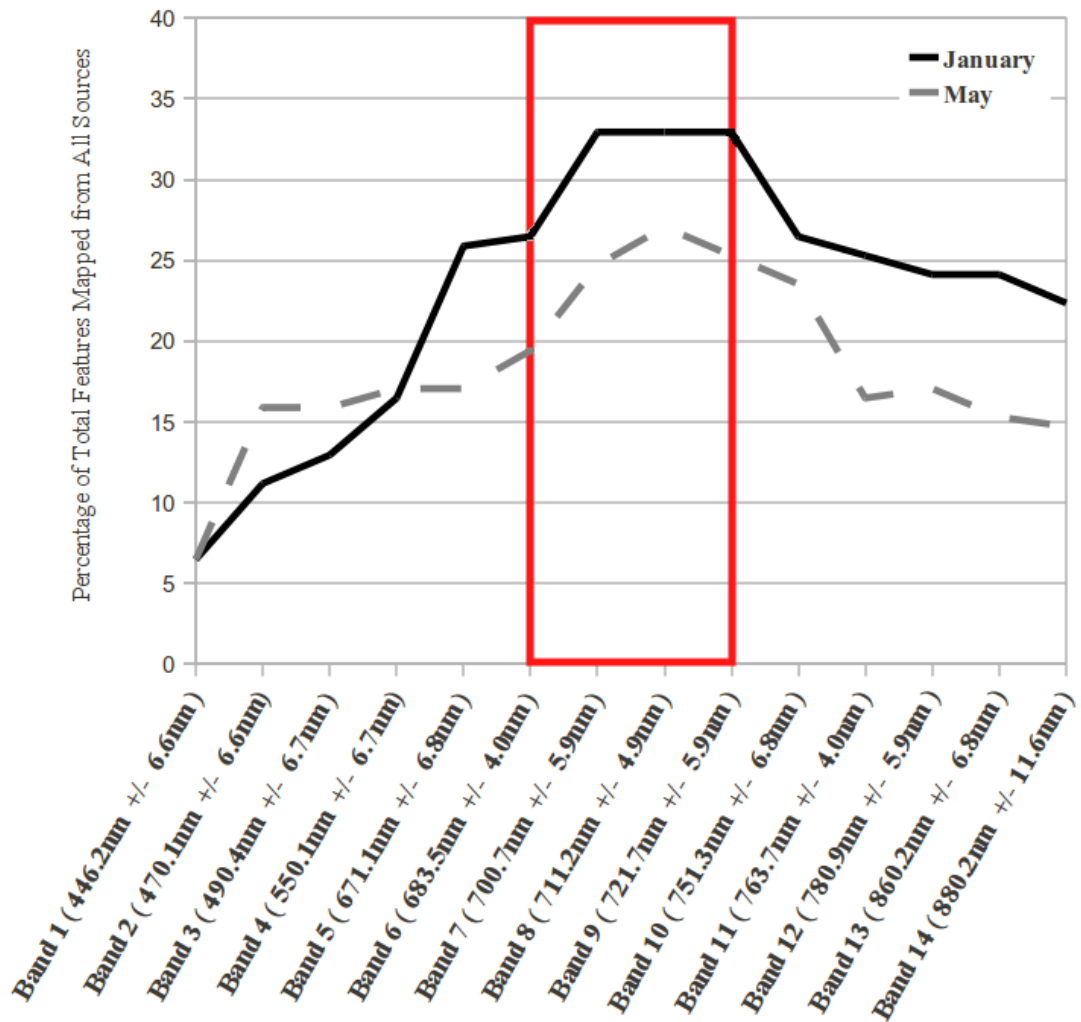
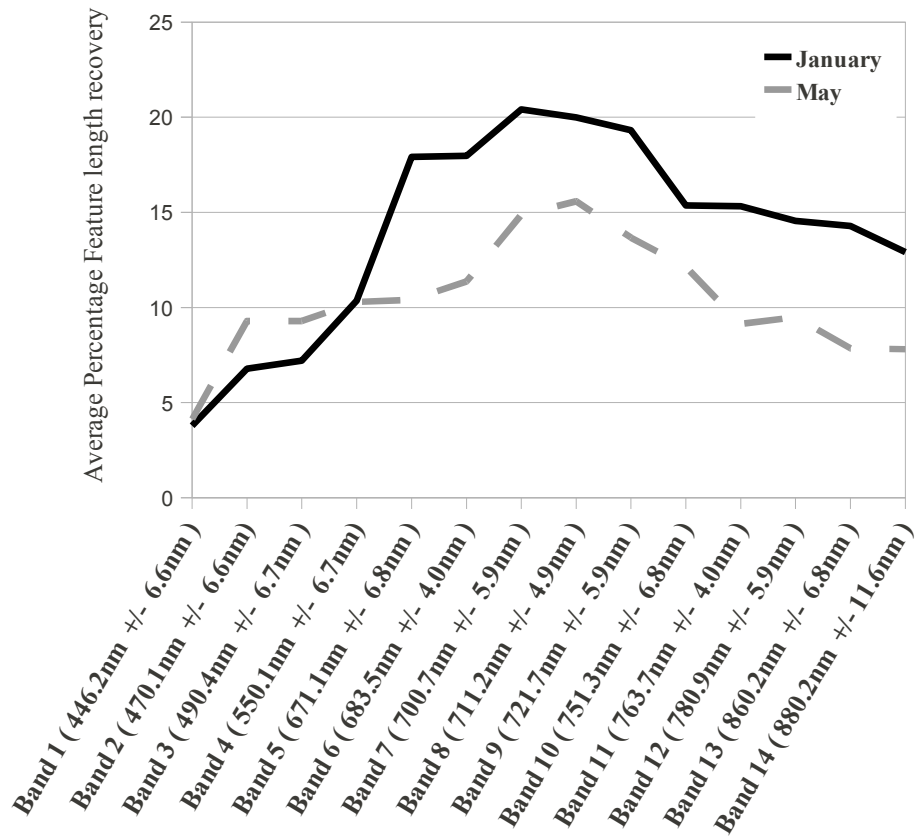


Figure 7.4: Feature recovery rates by band in the January and May spectral data (red outline denotes the red-edge wavelengths)

In figure 7.4 it can be seen that while the visibility of features varied dependant on the wavelengths viewed, the pattern of detection followed that of a typical vegetation response with a peak in visibility over the red edge (680-730nm) wavelengths for both January and May. In May this was also accompanied by a small peak in the green wavelength range (470-490nm) that again reflects the typical spectral response of growing vegetation (as indicated by chlorophyll quantity) at this time of year. This peak in the green region was not visible in the January data as the vegetation is senescent at this time of year.

This indicates that archaeological features were primarily detected in the spectral data due to proxy changes in vegetation rather than soil, which would have resulted in increased reflectivity (and therefore predicted increased visibility of archaeological features) in wavelengths over 800nm. The graph may also indicate why the vertical aerial photography averaged NIR band of 690nm-1000nm does not appear to be as sensitive to vegetation change, as the number of features visible in both seasons peaks sharply in the red-edge region and reduces as the wavelength increases through the NIR range.

The percentage recovery of features (APFL) from the individual CASI bands was also analysed using Friedman's ANOVA which ranks non-parametric data by mean recovery (figure 7.5). The mean values for each band are presented in table 7.3. It can be seen that in terms of APFL, the four NIR bands (6-9) from the January data provide the best recovery, followed closely by a single NIR band (8) from the May data. However, statistically both band 5 and band 10 of the January data performed better than the other NIR bands from the May flight. Overall it can also be seen that the January data outranks the May data for every band except 2 and 3; a result that directly mirrors the binary feature recovery rates in figure 7.4.



Band	APFL	Friedman Test Ranks
J_band7	20.41	16.27
J_band8	19.99	16.19
J_band9	19.32	16.09
J_band6	17.96	15.60
M_band8	15.58	15.50
J_band5	17.92	15.49
J_band10	15.36	15.24
M_band7	14.87	15.20
M_band9	13.67	15.10
J_band11	15.33	15.01
J_band12	14.55	14.98
M_band10	12.13	14.89
J_band13	14.29	14.86
J_band14	12.91	14.59
M_band6	11.37	14.47
M_band5	10.40	14.14
M_band4	10.29	14.10
M_band12	9.49	14.07
J_band4	10.36	13.96
M_band2	9.29	13.81
M_band3	9.29	13.81
M_band11	9.14	13.80
M_band13	7.85	13.79
M_band14	7.80	13.70
J_band3	7.20	13.23
J_band2	6.78	13.09
M_band1	4.14	12.54
J_band1	3.79	12.49

Table 7.3: Friedman's ANOVA ranking for percentage recovery of Average Percentage Feature Length from the January (J_) and May (M_) archive spectral data (Everleigh)

Figure 7.5: Average Percentage Feature Length in the January and May spectral data (Everleigh)

7.4.3 Comparing Land Use and Visibility in the Single Band Data

To further analyse the potential causes of difference between the data, the visibility of features was analysed by land use. For the January data it can be seen that the number of features is greater than that in May for all land use types except the area of minimal cultivation (figure 7.6). Table 7.4 gives the detailed land use notes for each of the categories. The area of minimal cultivation describes a field that is a scheduled monument that has no discernible plough damage and is used as pasture rather than hay production (in contrast to the disturbed grassland category). The area of heaviest cultivation (cultivation to a depth of $> 0.25\text{m}$) was characterised by bare earth in the January data and by a germinating crop in the May data.

Pearson's chi-squared statistic was used to test if there was a relationship between the land use and visibility of features in the spectral data, with the Cramer's V statistic indicating the strength of the relationship (or how likely it was to have occurred by chance) (Field 2009:695). For this test the expected count of each category has to be greater than five so the features mapped in undisturbed grassland, which numbered just five in total were excluded.

Land Use Category	Area Specific Notes
cultivation to a depth $>0.25\text{m}$	Currently in under cultivation as part of an arable regime. Heavily plough damaged.
minimal cultivation	Scheduled monument used as long pasture. Possibly historically cultivated (schedule includes a medieval stock enclosure) but never intensively
disturbed grassland	Grassland and hay pasture, possibly previously cultivated intensively but with limited plough degradation
undisturbed grassland (<i>not included in statistical analysis</i>)	Natural' chalk grassland, never subject to intensive agricultural methods.

Table 7.4: Detailed explanation of land use categories used in the Everleigh area.

The test showed that there was a significant association with land use and visibility in both sets of spectral data. In January the significance of the association was high with the chi-squared statistic $\chi^2 = 14.87$, $p < 0.001$ with a Cramer's V measure of 0.3 indicating that the association was unlikely to have occurred by chance. For the May data $\chi^2 = 12.42$, $p < 0.05$ with a Cramer's V measure of 0.27 indicating that this result is also unlikely to have occurred by chance despite the lower significance. This indicates that in areas of minimal cultivation, disturbed grassland and cultivation of $> 0.25\text{m}$, land use impacted on visibility in a significant way for both spectral datasets.

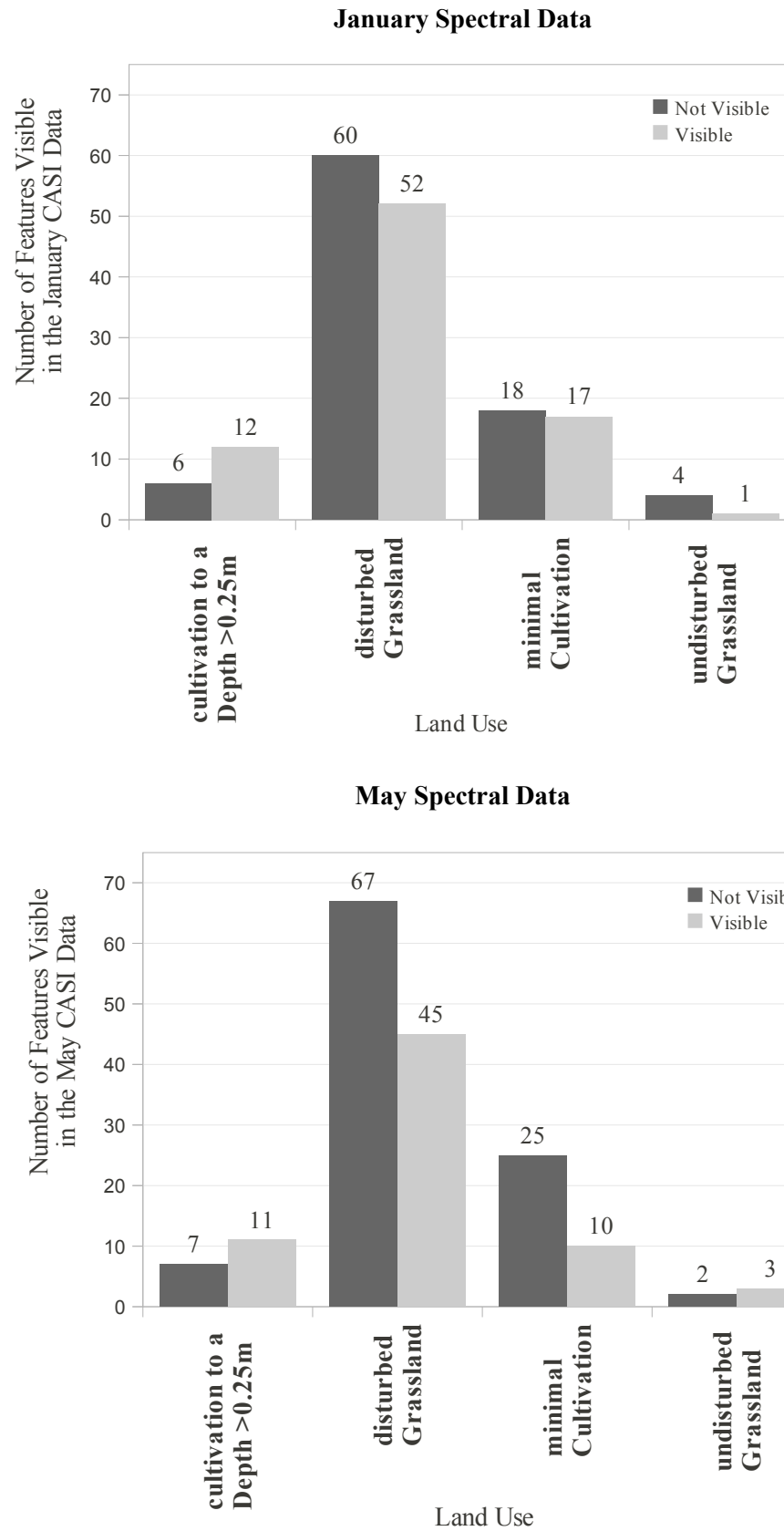


Figure 7.6: The number of features visible and not visible by land use from the spectral data

7.4.4 *Digital Combination of Spectral Bands*

While the analysis of single bands of the spectral data was of key importance for determining the most important areas of the spectrum for mapping archaeological features (Objective 8), it is a time consuming method that creates large amounts of redundancy; for a total number of 66 individual archaeological features in the January spectral data no less than 545 geospatial transcriptions were made. Consequently, it is necessary to investigate ways of analysing the spectral data to maintain the information that is archaeologically relevant while reducing the time invested in mapping.

7.4.5 *True and False Colour Composites*

Overall the level of complementarity among the bands was high with low numbers of features seen in only one band (termed here as “unique” features), nevertheless it was possible to use this method to identify a potentially useful FCC band combination for January as the bands met the caveats of having good feature recovery and wide spectral coverage. Table 7.5 shows the bands which had “unique” features ranked by the total number of features mapped in them (all other bands had features that were shared with at least one other band). Discounting band 8 due to its close spectral proximity to band 7 (and its lower number of unique features) left three bands (3, 7 and 14) which represent uniqueness in the archaeological data and have broad spectral coverage.

For the May data the situation was more complex with unique features trending towards the lower wavelengths in bands 1, 2 and 3 and an even spread of single “unique” features across much of the NIR and red region. A colour composite comprised of bands 1, 2 and 3 would not only be spectrally limited, but as these bands returned low number of feature, would result in much of the archaeological data not being visible in the image. The band selection therefore had to incorporate a weighting for the total number of features mapped and a broad coverage of the electromagnetic spectrum. In this instance bands 3, 8 and 12 were selected to provide an optimal mix of uniqueness, feature recovery and spectral coverage. Figure 7.7 shows the comparison of the TCC and FCC against the recovery rates for the best performing single bands.

January CASI Data Band	no. of unique features	No. of features (max 111)	May CASI Data band	No. of unique features	No. of features (max 74)
Band 7 (c.700.7nm)	4	111	Band 3 (c.490.4nm)	3	51
Band 8 (c.711.2nm)	1	109	Band 2 (c.470.1nm)	2	26
Band 14 (c.880.2nm)	1	76	Band 1 (c.446.2nm)	1	17
Band 3 (c.490.4nm)	1	51	Band 4 (c.550.1nm)	1	53
			Band 8 (c.711.2nm)	1	74
			Band 9 (c.721.7nm)	1	68
			Band 7 (c.490.4nm)	1	67
			Band 12 (c.780.9nm)	1	56
			Band 11 (c.763.7nm)	1	55

Table 7.5: Number of unique features in the digital spectral data

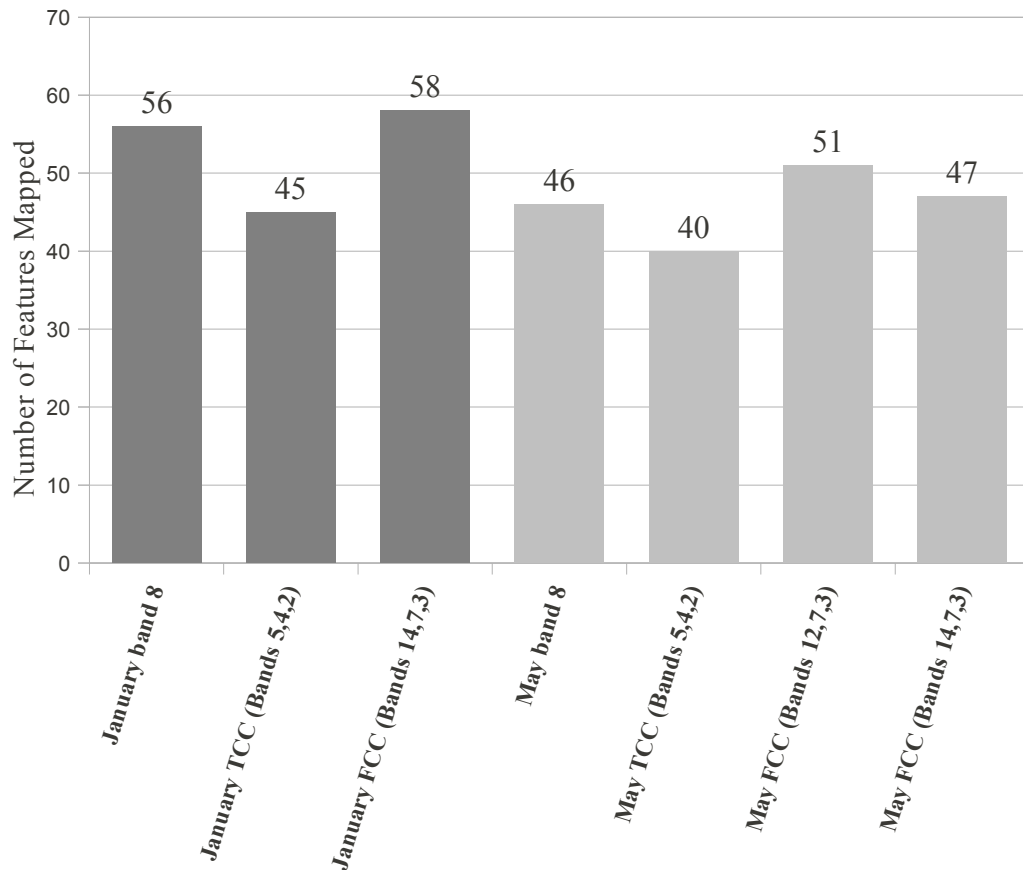


Figure 7.7: The relative feature recovery rates from the true and false colour composites of the January and May spectral data

As can be seen from Figure 7.7, mapping from a TCC image alone revealed fewer features in both the January and May data, a result which was to be expected given the higher sensitivity of the NIR bands to archaeological features as discussed in section 7.4.2. The FCC of the January data allowed two more features to be mapped when compared with from the best performing single band. In May the number of features was slightly greater with five features extra features being mapped from the optimal FCC band combination (bands 12,7 and 3) compared with the best performing single band. As the optimal FCC for May was difficult to define by the parameters described in the method section, a second FCC using the optimal parameters of the January spectral data was also mapped for comparison. This FCC (bands 14, 7 and 3) performed better than the TCC but only marginally better than the single band data and significantly worse than the optimised FCC of bands 12, 7 and 3. These results indicate the importance of applying a FCC that is sensitive to the distribution of unique features across the spectral bands. Additionally they show that the optimal combination of wavelengths used for the FCC varies by season.

7.4.6 Principal Components Analysis (PCA)

PCA was used to reduce redundancy in the spectral data; the results of the transformation can be seen in table 7.6 in terms of the percentage variance of the full data set that is captured by each component. It can be seen that in all cases the first three components account for over 99% of variation. This result is mirrored by the archaeological feature mapping exercise where no features could be identified in PCs 4-14.

The combined results of the principal components mapping using all 14 spectral bands provided an improvement to feature recovery rates compared with single band analysis (figure 7.8).

Principal Component	January 14 Band % Variance	May 14 Band % Variance	January FCC % Variance	May FCC % Variance
1	93.68%	96.94%	93.28%	97.01%
2	5.92%	2.79%	6.53%	2.90%
3	0.18%	0.09%	0.19%	0.09%
4	0.12%	0.09%		
5	0.05%	0.04%		
6	0.02%	0.03%		
7	0.01%	0.01%		
8 to 14	0.00%	0.00%		

Table 7.6: Variation represented by the Principle Components Analysis of the Everleigh spectral data.

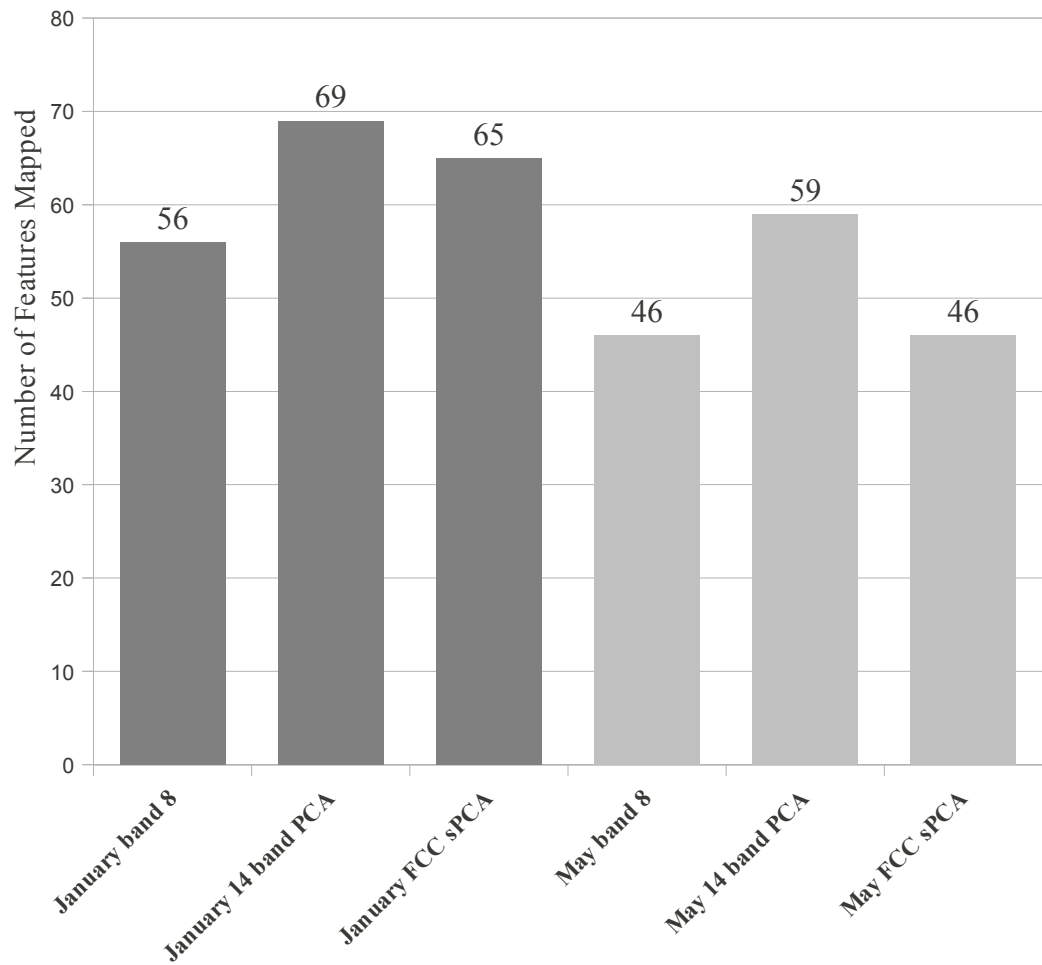


Figure 7.8: Relative feature recovery rates from the Principle Components Analysis and selected Principle Components Analysis of the January and May spectral data

sPCA was also undertaken using the three bands of the FCC for each dataset. This showed that for the January data more features were mapped from using the sPCA than by mapping directly from the FCC but that this technique did not out-perform the use of all spectral bands for the sPCA. For the May data the sPCA showed less features than were mapped from the false colour image.

The uniqueness of features across these four visualisations was also investigated to assess whether the higher recovery rates of the PCA included all features seen in the best single band and FCC imagery. As can be seen from table 7.7, the 14 band PCA approach for the January data was the most encompassing of the data reduction techniques but still did not capture six unique features. The detailed records of the features that were not recorded are shown in table 7.8, and while the numbers involved are too small to determine if there is a pattern in terms of feature type or land use, at least one feature is mapped in all three other sources (UID 112).

	Number of Features visible in other techniques			
	14 band PCA	FCC sPCA	FCC (14, 7, 3)	Band 8
14 band PCA	0	4	2	2
FCC PCA	8	0	3	5
FCC (14, 7, 3)	13	10	0	7
Band 8	15	14	9	0

Table 7.7: Cross tabulation of features detected between the 14 band Principle Components Analysis, selective Principle Components Analysis, False Colour Composite and Band 8 of the January spectral data.

UID	Interpretation	Land Use	14 band PCA	FCC sPCA	FCC (14, 7, 3)	Band 8
112	lynchet	minimal cultivation	0	1	1	1
113	lynchet	minimal cultivation	0	1	0	0
400	Linear feature	disturbed grassland	0	0	0	1
621	bank	minimal cultivation	0	1	0	0
638	ditch	disturbed grassland	0	1	0	0
815	veg?	disturbed grassland	0	0	1	0

Table 7.8: Detail of features not mapped by the 14 band Principle Components Analysis of the January spectral data (where 0 denotes not present, 1 present)

Table 7.9 shows the numbers of features not mapped by the PCA in the May spectral data. It can be seen that the performance of the PCA is slightly worse in the May data with a total of eight features that were not visible in the PCA but were mapped from one of the other methods.

Unlike the January data, all of these features were mapped from the single analysis of band 8 (table 7.10), indicating that for this dataset the 14-band PCA may be masking important data from key spectral regions that are known to contain high numbers of archaeological features (see table 7.9).

	Number of Features not visible but seen in other techniques			
	14 bands PCA	FCC sPCA	FCC (12, 7, 3)	Band 8
14 bands PCA	0	3	4	8
FCC PCA	16	0	6	17
FCC (14, 7, 3)	12	1	0	13
Band 8	21	17	18	0

Table 7.9: Cross tabulation of features detected between 4 band Principle Components Analysis, selective Principle Components Analysis, False Colour Composite and Band 8 of the May spectral data.

UID	Interpretation	Land Use	14 Bands PCA	FCC sPCA	FCC (12, 7, 3)	Band 8
112	lynchet	minimal cultivation	0	0	0	1
115	lynchet	cultivation to a depth >0.25m	0	0	1	1
148	lynchet	disturbed grassland	0	0	0	1
853	lynchet	disturbed grassland	0	0	0	1
864	Unknown	disturbed grassland	0	0	0	1
865	lynchet?	disturbed grassland	0	0	0	1
872	unknown	minimal cultivation	0	0	0	1
898	Unknown	disturbed grassland	0	1	1	1

Table 7.10: Detail of features not mapped by the 14 band Principle Components Analysis of the May spectral data (where 0 denotes that the feature was not found)

In addition, Friedman's ANOVA was used to compare the results of the 14 band PCA, sPCA of the FCC, FCC and Band 8 by average percentage recovery of feature length (section 6.18.4, tables 7.11 and 7.12). This showed that there was a significant difference between the visualisation techniques in terms of the length of the archaeological features that was detectable, with the 14 band PCA ranking the most highly. This statistical analysis shows that, in this study, the 14-band PCA returns a significantly larger proportion of the archaeological features mapped (measured by length) than the other techniques tested.

January Spectral Data Descriptive Statistics

	N	Mean
FCC (14,7,3)	170	25.13
Band 8	170	19.99
TCC	170	15.95
PCA 14 bands	170	29.27

Friedman Test

	Mean Rank
PCA 14 bands	2.71
FCC (14,7,3)	2.62
Band 8	2.39
TCC	2.27

Test Statistics	
N	170
chi-square	51.05
df	3
Asymp. Sig.	0.00

Table 7.11: Friedman's ANOVA for the Average Percentage Feature Length in the January spectral data True Colour Composite, False Colour Composite and Principle Components Analysis

May Spectral Data Descriptive Statistics

	N	Mean
FCC (14,7,3)	170	21.26
Band 8	170	15.58
TCC	170	13.11
PCA 14 bands	170	22.30

Friedman Test

	Mean Rank
PCA 14 bands	2.66
FCC (14,7,3)	2.63
Band 8	2.41
TCC	2.29

Test Statistics	
N	170
chi-square	35.28
df	3
Asymp. Sig.	0.00

Table 7.12: Friedman's ANOVA for the Average Percentage Feature Length in the May spectral data True Colour Composite, False Colour Composite and Principle Components Analysis

In summary, while the 14 band PCA worked well in terms of numbers of features recovered and the percentage length of features recovered, comparison with the FCC and best performing single band illustrates that the technique may potentially eliminate relevant data from wavelengths that were shown to be of importance for the visibility of archaeological features. In addition the PCA of FCC bands was not seen to out-perform the FCC image in every instance showing potential loss of archaeological feature visibility when the spectral data are transformed.

7.4.7 Comparing Vegetation Indices

The results of the calculation of vegetation indices for the Everleigh spectral data are shown in figures 7.9 and 7.10. The number of features detected are shown against the results of the 14 band PCA and best performing single band for comparison (section 7.4.2).

The analysis shows that while none of the vegetation indices outperform the single band analysis or 14 band PCA, some may be useful for visualising archaeological features in this environment. In particular the MRESRI narrowband greenness index performed well in both seasons (figures 7.9- 7.10). Also worthy of note is the poor performance of the NDVI for both datasets despite it being the most commonly applied index (Section 3.10.3).

The vegetation indices were also compared on a feature-by feature basis with the 14 band PCA analysis and the best performing band to determine whether they were able to record significant numbers of additional features (Tables 7.13 and 7.14). It can be seen from these tables that several of the indices added to the number of features mapped using the 14 band PCA (MRESRI, SRI, MRENDVI). In direct comparison to the features mapped from the best performing band it can also be seen that several of the indices allowed the mapping of additional features. It is also notable that a number of the indices did not add any further features to those known from the 14 band PCA or NIR single band analysis (REPI, EVI).

To summarise the efficiency of each of the indices more clearly , a ranked scoring system has been used to compare uniqueness with both the PCA and NIR and the total number of features. The results of this scoring system are compiled in table 7.15. The two strongest performing vegetation indices, MRESRI and MRENDVI in January belong to the narrowband greenness category with the ARI2 leaf pigment index ranking third. In May the SRI broadband greenness index proved the most useful, scoring slightly higher than the MRESRI, a result that may be a reflection of the lower prominence of the red-edge wavelengths in this dataset (see Figure 7.4). The third best performing index for this data set was the SIPI, light use efficiency index. The best performing index across both seasons is the narrowband greenness index MRESRI. The well-used broadband NDVI index was seen to perform very poorly for both datasets on all

criteria in the assessment, an indication of its lower suitability for spectral data with high spectral resolution when compared with the narrowband indices.

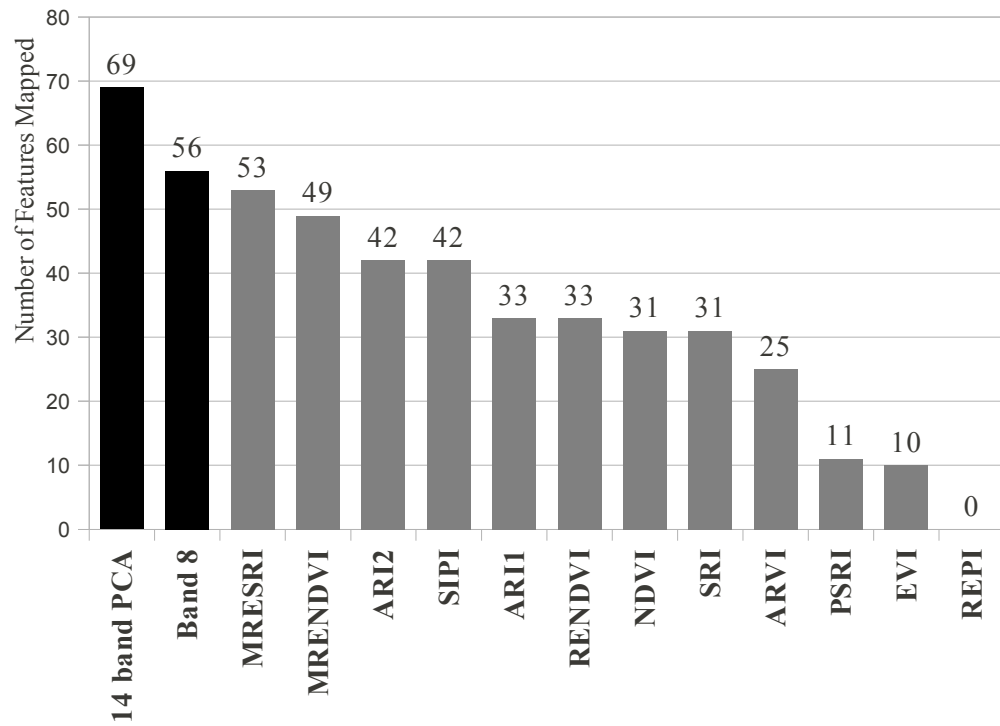


Figure 7.9: Chart showing the relative feature recovery rates from the vegetation indices applied to the January spectral data

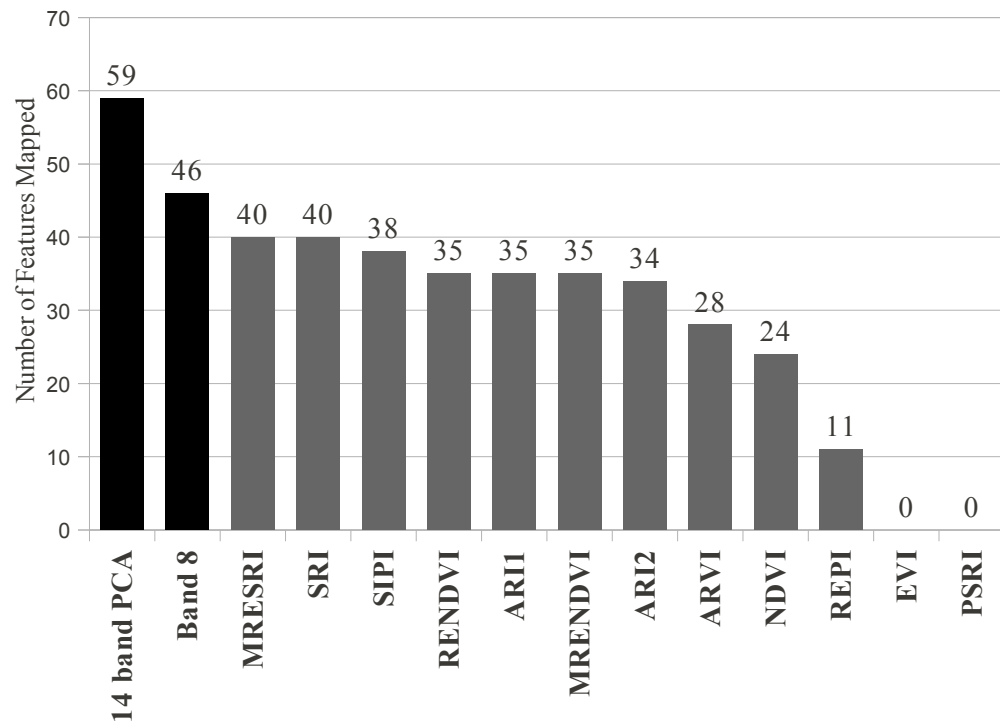


Figure 7.10: Relative feature detection rates from the vegetation indices applied to the May spectral data

January Spectral Data

Vegetation Index	14 band PCA	Band 8	TCC	FCC (14,7,3)
MRESRI	6	14	22	11
SRI	4	6	9	5
MRENDVI	1	9	16	7
ARI2	1	7	14	5
SIPI	1	7	15	6
RENDVI	1	6	10	4
ARI1	1	6	10	4
ARVI	1	5	8	5
NDVI	1	5	8	4
PSRI	0	2	2	2
EVI	0	1	2	2
REPI	0	0	0	0

Table 7.13: Cross comparison table of the vegetation indices applied to the January spectral data showing number of extra features mapped per index compared with with best performing visualisation methods

May Spectral Data

Vegetation Index	14 band PCA	Band 8	TCC	FCC (12,7,3)
SRI	5	13	16	9
MRESRI	4	11	15	8
MRENDVI	2	11	12	6
ARI1	2	10	11	5
RENDVI	2	10	12	6
NDVI	2	9	9	2
ARVI	2	8	9	5
SIPI	1	14	15	9
ARI2	1	11	14	5
REPI	1	4	3	1
EVI	0	0	0	0
PSRI	0	0	0	0

Table 7.14: Cross comparison table of the vegetation indices applied to the May spectral data showing number of extra features mapped per index compared with with best performing visualisation methods

<i>January</i>	PCA score	Red-edge (band 8) Score	No. of features Score	Final Score
MRESRI	12	12	12	36
MRENDVI	7	11	11	29
ARI2	7	9	9	25
SIPI	7	9	9	25
SRI	11	7	5	23
RENDVI	7	7	7	21
ARI1	7	7	7	21
NDVI	7	4	5	16
ARVI	7	4	4	15
PSRI	2	3	3	8
EVI	2	2	2	6
REPI	2	1	1	4

<i>May</i>	PCA Score	Red-edge (band 8) Score	No. of features Score	Final Score
SRI	12	11	11	34
MRESRI	11	9	11	31
SIPI	4	12	10	26
MRENDVI	8	9	8	25
ARI1	8	6	8	22
RENDVI	8	6	8	22
ARI2	4	9	6	19
ARVI	8	4	5	17
NDVI	8	5	4	17
REPI	4	3	3	10
EVI	1	1	1	3
PSRI	1	1	1	3

Table 7.15: Scoring of vegetation indices for January and May based on uniqueness (compared to 14 band Principle Components Analysis and single best performing band) and total number of features visible.

7.5 Spectral Data Processing (Upavon)

7.5.1 Introduction

The hyperspectral data for Upavon were specified for collection in the first quarter of 2010 based on the results of the study of the archive data for Everleigh presented in section 7.4. The primary aim of the analysis was to identify regions of spectral sensitivity across the wavelengths recorded and compare these with the sensitivity results of the single band analysis of the archive data (Objective 8). Additionally it was possible to address Objective 11 with these data as contemporary geophysical and soil moisture measurements were collected on the day of the flight. The results below focus on the assessment of spectral sensitivity. The correlation of spectral data and ground observations is detailed in Chapter 8 (section 8.3).

7.5.2 Separation Index (SI)

The first stage of the up-scaling of the SI from a single field (as in the original application (Cavalli *et al.* 2009)) to a wider landscape area required an assessment of the homogeneity of the background spectral response across the area (section 6.8.1). The comparison of the spectral response of five sub-areas to the total area gave a standard error of 0.004nm across the spectrum, so homogeneity was assumed.

The first application of Cavalli *et al.*'s (2009) calculation for assessing spectral separability of known archaeological features revealed some issues that were not clarified in the original publication. These are detailed along with the resolutions in table 7.16, and led to the modification of the SI as detailed in section 5.7.

Issue	Resolution
The range of the spectral values impacted the output of the index	Convert floating point FLAASH corrected .bil format into radiance by dividing by 10000
The ratio of archaeological pixels to background pixels impacted the output of the index	Addition of a weighting factor (ratio of archaeological and background pixels)
Noisy bands not removed by FLAASH (at the edge of the water absorption regions for example) impacted the output of the index	Noisy bands adjacent to water absorption regions removed from the analysis.

Table 7.16: Issues with the original Separation Index and the resolutions applied as part of this study

Once the index had been modified to make it fit for purpose (see section 6.8.1) it was possible to compare the separability of the feature categories across the spectrum of wavelengths (figure 7.11). The average separability and standard deviation for each feature type is given in table 7.17. Separability does not have a unit but is scaled between 0 and 100 so can be thought of in the same manner as a percentage.⁹

	Negative Features	Positive Features	No Topography	Control Sample
mean	20.34	49.16	6.69	1.34
SD	8.58	23.35	2.80	0.66

Table 7.17: Mean and Standard Deviations for the four categories of features assessed with the Separation Index

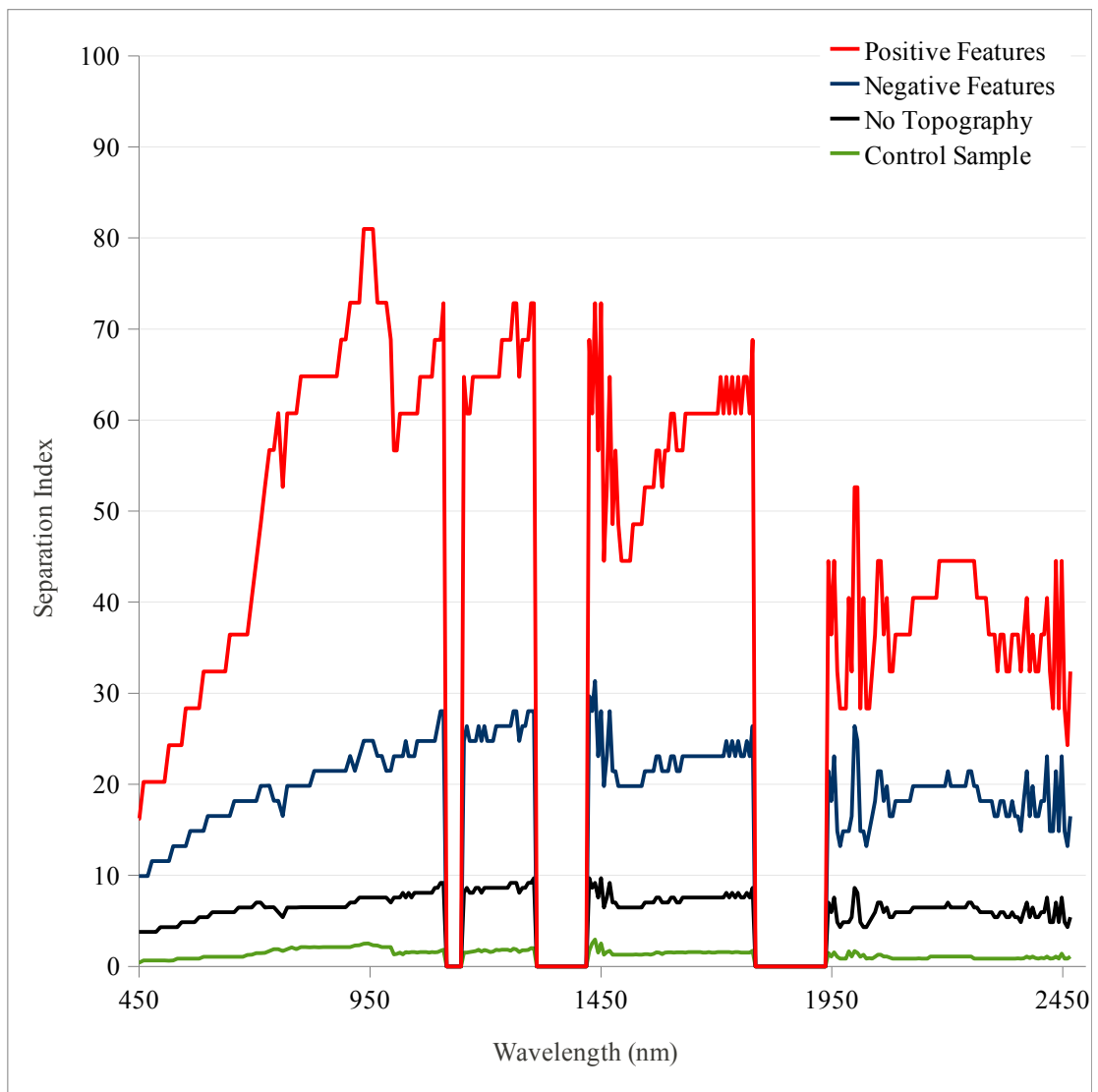


Figure 7.11: Results of the Separation Index calculation across the Eagle / Hawk hyperspectral data

⁹ Where the separability value is referenced it is prefaced with (SI)

The first result of note is that the separability of the control features is very low (mean SI 1.34). This gives a clear indication of the validity of the index for measuring the separability of 'real' features, although there are some regions of the spectrum (~950nm for example) that appear to be affected by noise within the data, either associated with water absorption or the overlap region of the two sensors.

The second factor to consider is the difference in separability between archaeological features grouped by their topography. In this data, positive features were far more separable from the background (mean SI 49.16) than negative features (mean SI 20.34). It was also seen that the features with no detectable topography (in the contemporary high resolution ALS data) were more separable from the background than the control sample although overall their separability was very low across the spectrum (mean SI 6.69). This result has implications for the identification of features that do not have physical traces in this environment, showing that while detection might be possible features only represented by soil or vegetation change are five times less distinct from the background than those with positive topography. This more detailed analysis belies the assumption of the original authors that all types of archaeological feature are equally detectable (Cavalli et al. 2009).

In terms of spectral sensitivity as reflected in the SI score, it can be seen that the NIR region performs the most strongly. This compares broadly with the results seen in the archive multispectral data (section 7.4.3). To analyse the data further, the 90th percentile of most separable bands were extracted and are illustrated in figure 7.12. For positive features the 90th percentile threshold was SI 70 while for negative features the 90th percentile lay at SI 26. Features with no extant topography were excluded at this stage due to their very low separability.

The bands with the most separability show different trends dependant on the feature type. For positive features in this area, the highest separability was in three broad regions 907-985nm, 1109-1147nm and 1299nm-1336nm and one narrow region at 1785-1791nm. For negative features the highest separability was mostly in two regions: 1109-1147nm and 1261-1450nm.

The combined high separability (figure 7.13) was calculated from the overlapping regions of 90th percentile SI for both feature types and gives an indication of the ranges that might be expected to provide the best separability of both types of archaeological topography. This shows two broad regions of optimum separability, 1103-1160nm and 1280-1469nm. This grouped separability must be treated with caution however, as it is known that features with negative topography were less than half as separable from the background than positive features, even in

the regions of highest separability (figure 7.11).

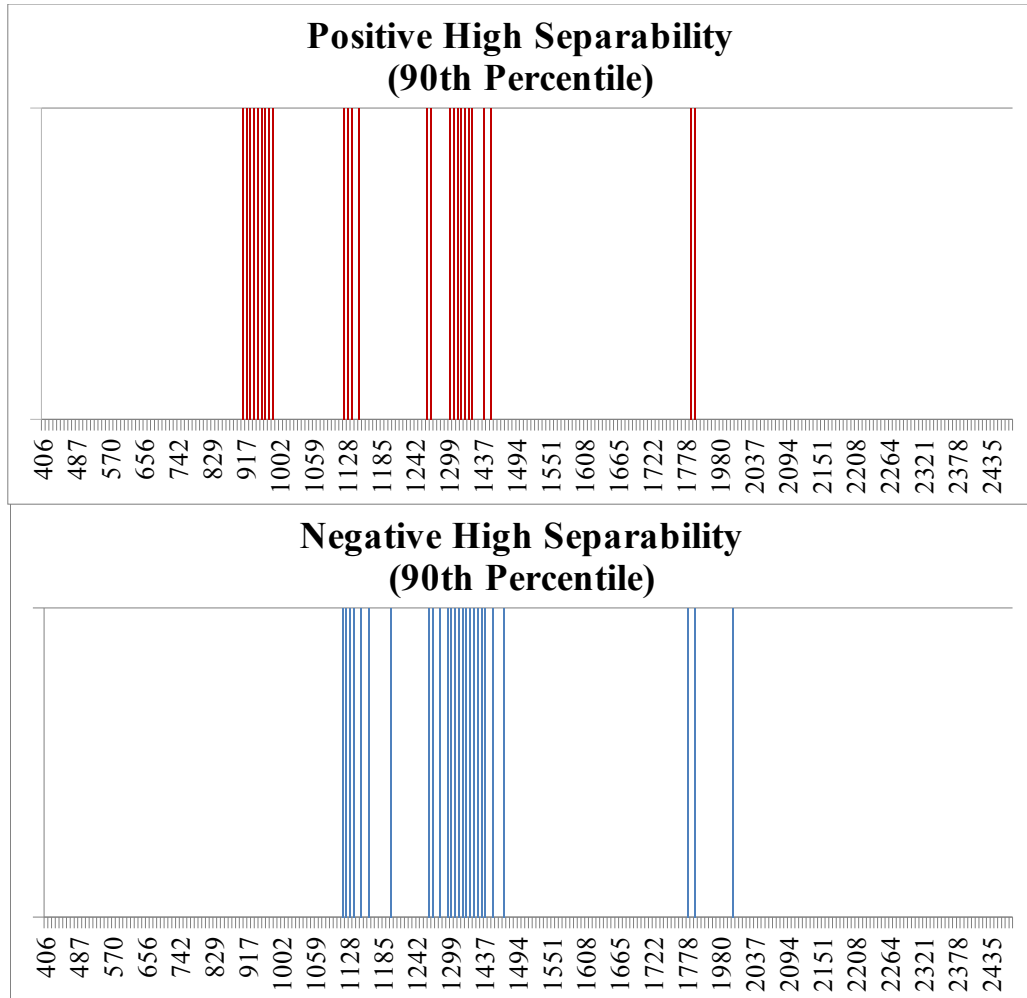


Figure 7.12: Spectral wavelengths with the highest separability (90th percentile)

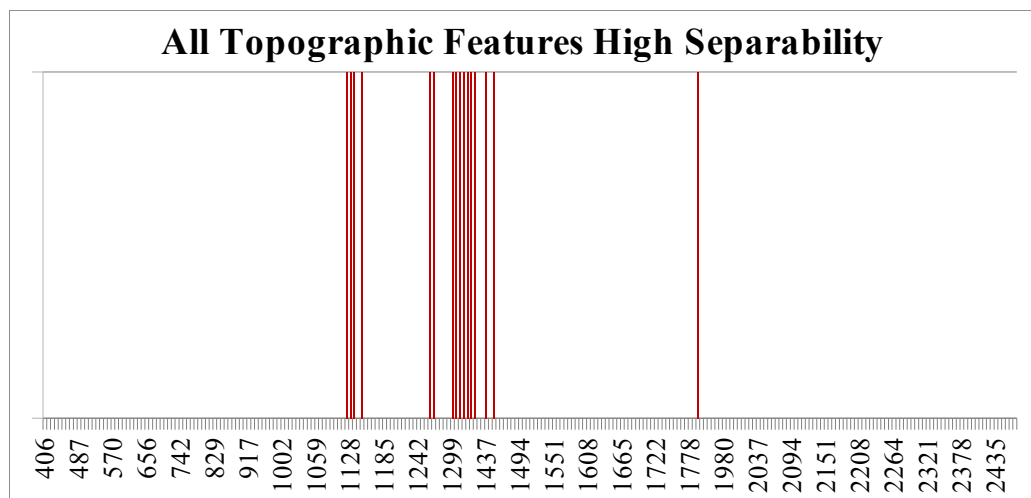


Figure 7.13: Spectral wavelengths most sensitive to all archaeological features in the study

area (overlap of key regions from figure 7.12)

7.5.3 Separation for Vegetation Indices

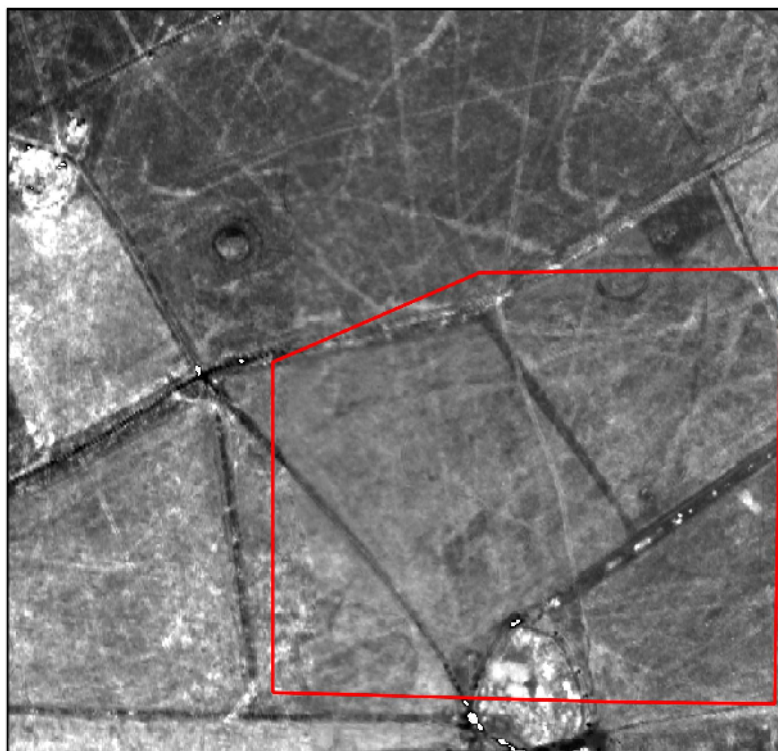
Following the successful application of the separability index to the hyperspectral image it was hypothesised that a similar technique could be used to compare the performance of vegetation indices in terms of feature separability. Unfortunately, due to the different scales of the indices it was not possible to standardise the SI for comparison among indices (the SI was shown to be heavily range dependant in the original application, section 7.5.2). This limitation contradicts the claim of the original authors that the SI can be used to compare different data despite the application of different processing techniques (Cavalli et al. 2009:274). This limitation also meant that comparison of vegetation indices to single bands using this technique was not possible.

Vegetation Index	Short Term	Negative Features SI	Positive Features SI	Range (theoretical)	Range (real)
Normalized Difference Vegetation Index	NDVI	17.78	24.09	-1-1	0-0.8
Modified Red Edge Normalized Difference Vegetation Index	MRENDVI	7.00	25.36	-1-1	0-0.97
Red Edge Normalized Difference Vegetation Index	RENDVI	16.85	25.36	-1-1	0-0.75
Enhanced Vegetation Index	EVI	17.78	24.09	-1-1	0-0.58

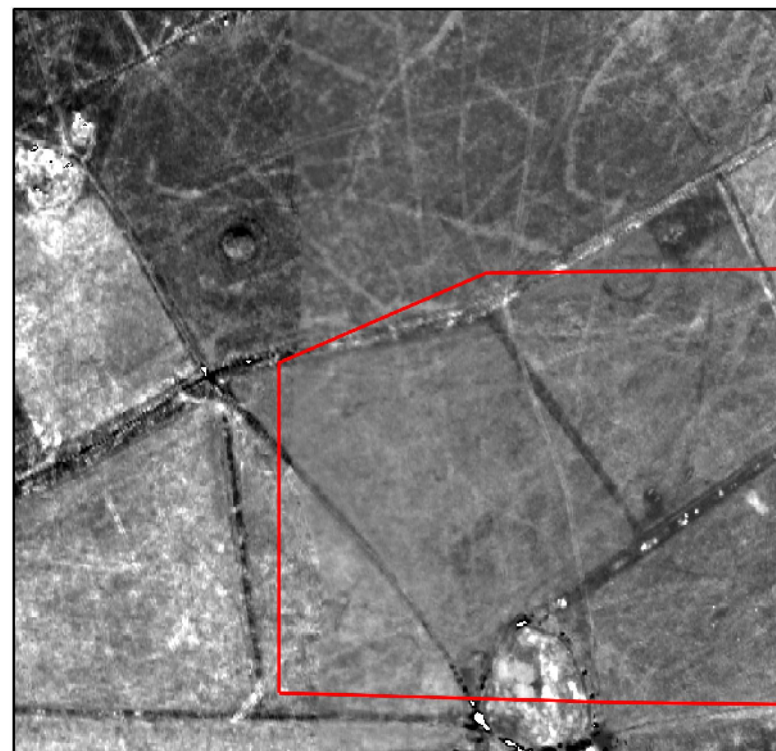
Modified Red Edge Simple Ratio Index	MRESRI	8.52	5.53	0-30	0-30
Simple Ratio Index	SRI	17.78	24.11	0-30	1-12.3

Table 7.18: Separability Index as applied to selected vegetation indices

As can be seen from table 7.18, even vegetation indices that are theoretically comparable in terms of range, in reality might have quite different values making the SI an inappropriate tool for data comparison. However the SI values do appear to mirror differences in feature detectability using manual interpretation of vegetation indices of comparable scale. Figure 7.12 shows the difference in manual interpretation of positive features (lynchets) in the red highlighted area between the SRI and MRESRI. As predicted by the SI, positive features in the MRESRI image are less detectable than in the SRI image. The SI calculations for the vegetation indices might also be of use to assess the likelihood of a feature type being detected by the index. For example, it could be inferred that in the NDVI image features with positive topography are almost 1.5 times more likely to be detectable than negative features. However it is clear that the SI should be applied with careful consideration of the range of the original image.



SRI image (positive feature SI 24)



MRESRI (positive feature SI 5)

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an Ordnance Survey / Edina supplied Service



0 200 m

Figure 7.14: Differential visibility of positive features (lynchets) between the SRI and MRESRI vegetation indices

ALS Data Processing

7.6 Archive ALS Data Results (Everleigh)

As documented in section 4.4.7, the archive data for the Everleigh Study Area was examined in two stages. First, a rapid assessment of Areas A and B (figure 7.1) was undertaken using individual shaded relief images. The results of this are given in section 7.6.3. Based on these results it was necessary to define a smaller representative subset (Area C, figure 7.1) upon which all further processing was performed (sections 7.6.4-7.6.9).

In total 123, or 72%, of the features seen in the Everleigh study Area C could be mapped to some extent from the ALS elevation data, by far the largest portion of features detected by any ARS data set used in the study. This section gives the results of the feature mapping from different ALS visualisation techniques (sections 7.6.1-7.6.7) and compares their efficiency both in terms of binary visibility and APFL (section 7.6.8). The penultimate section gives the results of the statistical analysis of the impact of land use on feature detectability in the ALS visualisations (section 7.6.9) while the final section attempts to metrically assess the effects of plough damage on feature degradation using ALS data (section 7.6.10)

7.6.1 Quality Assessment

The first step in analysing the ALS data was to calculate the point density and average point spacing. For the archive data the point density was calculated (for each flightline) as 0.69 hits per metre with an average mean distance between points of 1.21m. This relatively poor resolution constrained some of the analysis of the data. In particular, given the relatively low requirement to remove vegetation from the mostly open landscape, the application of filtering algorithms to remove vegetation was deemed unsuitable due to the reduction in resolution this type of filter would cause. The point data was interpolated to 1m resolution using the IDW method. All subsequent visualisation techniques were based on this raster.

7.6.2 Archive ALS Intensity Data

Only one archaeological feature (UID 425), was detected in the ALS intensity data for Everleigh (figure 7.15) and so this source was not incorporated in the feature mapping exercise. Consequently it was not possible to use these data to contribute towards Objective 10.

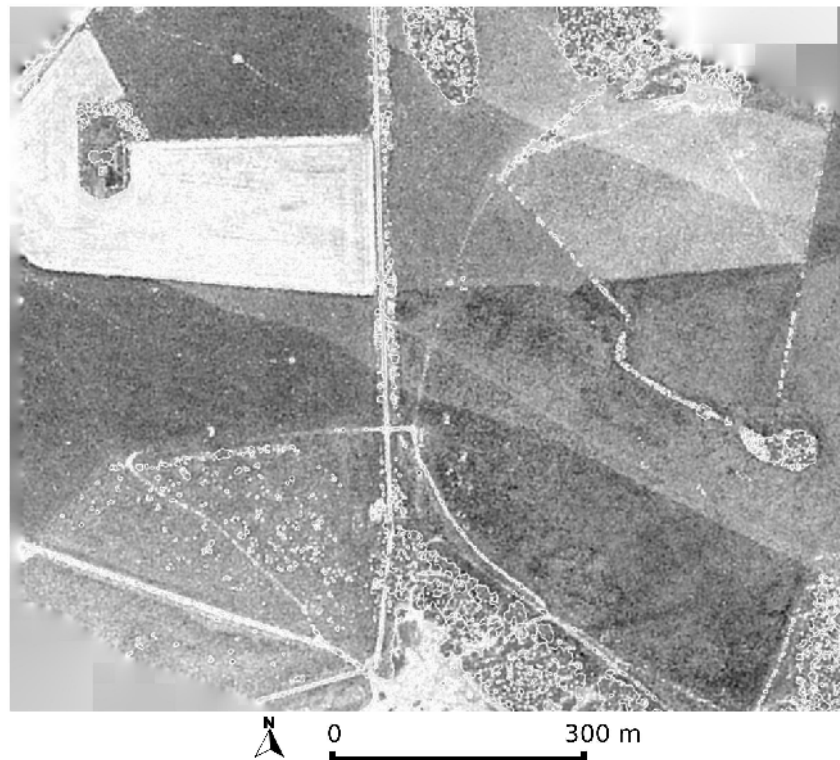


Figure 7.15: Airborne Laser Scan intensity image, Everleigh

7.6.3 Shaded Relief Images

The first technique used to visualise the ALS data was shaded relief mapping (section 3.11.5). The results presented here are from the initial assessment of Areas A and B (figure 6.1). The altitude and azimuth of the shading was first calculated using the default ArcGIS settings of 45° elevation and 315° east of north. The angle of elevation was then reduced to $<10^\circ$ which improved feature visibility by 6% in this landscape. The two images are compared in figure 7.16.

To examine the effects of illumination angle on the visualisation of features, eight separate shaded models were created at 45° intervals (figure 7.17). The results in table 7.19 show that there is a 12% difference in the number of features mapped between the best and worst performing angles, with the most effective angle for the Everleigh study area being 225° east of north. This was almost double the difference in features mapped through altering the altitude, illustrating the effect of illumination angle on this type of visualisation.

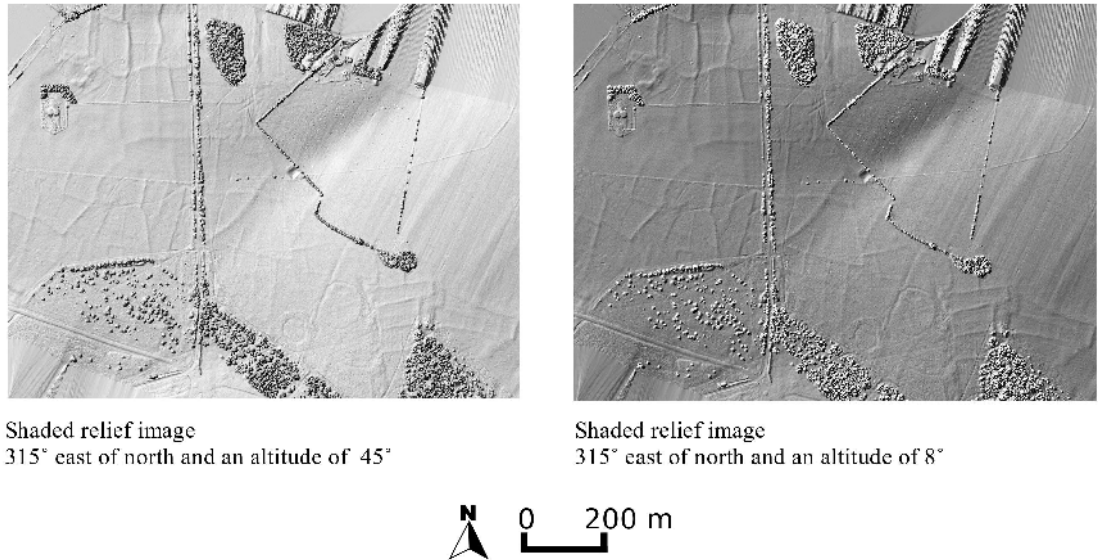


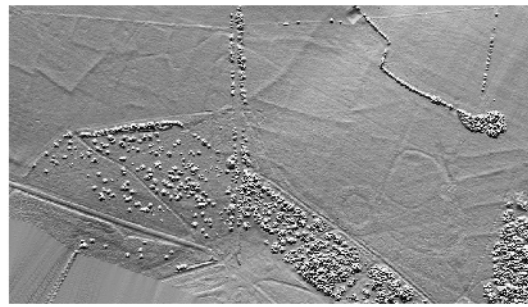
Figure 7.16: Images comparing the impact of the altitude of illumination on the visibility of archaeological features

Angle of Illumination (Degrees east of North)	0	45	90	135	180	225	270	315
Number of features mapped	277	309	289	273	276	313	309	273

Table 7.19: Number of features mapped for each angle of illumination east of north on the ALS shaded relief models.

7.6.4 PCA of Shaded Relief Images

As with the spectral data, it was necessary following the initial mapping from shaded relief images, to select a representative sample area for detailed analysis (Area C, figure 6.1). Once this area had been selected, a Principal Components transformation could be undertaken on the shaded relief images as proposed by Devereux et al. (2008). This technique is intended to reduce dimensionality of the shaded relief data, but results in a number of files with decreasing levels of information. For the Everleigh data only the first two Principal Components contained unique archaeological information (table 7.20). In order to access the full number of features the results of PC 1, 2 and 3 had to be manually combined in order to create PC All, a process that when combined with the mapping from multiple rasters made this technique rather time consuming in comparison to the others utilised. The comparison feature detection from the PCs with the HER is given in figure 7.18. Table 7.20 gives the number of features that were not recorded in the other PCs, showing that the number of new features diminished with each component.



Shaded relief from 0° east of north



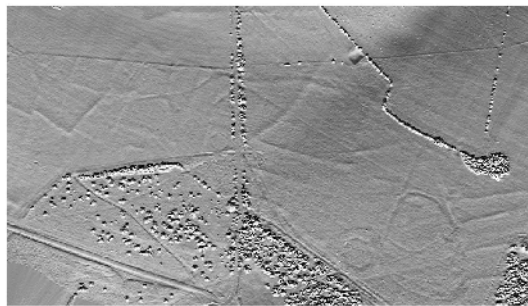
Shaded relief from 45° east of north



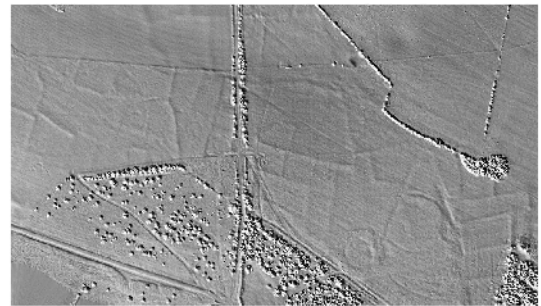
Shaded relief from 90° east of north



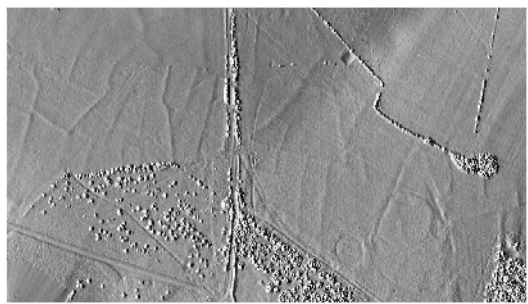
Shaded relief from 135° east of north



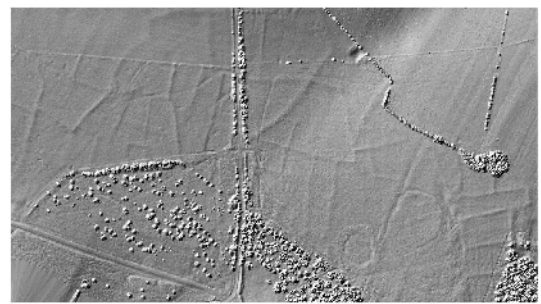
Shaded relief from 180° east of north



Shaded relief from 225° east of north



Shaded relief from 270° east of north



Shaded relief from 315° east of north



0

500 m



Figure 7.17: Variation of illumination angle at 45° intervals in shaded relief models

Number of features not recorded by other PCs	Jan PC 1	Jan PC 2	Jan PC 3
	17	7	4

Table 7.20: Number of features not recorded by the Principle Component transforms

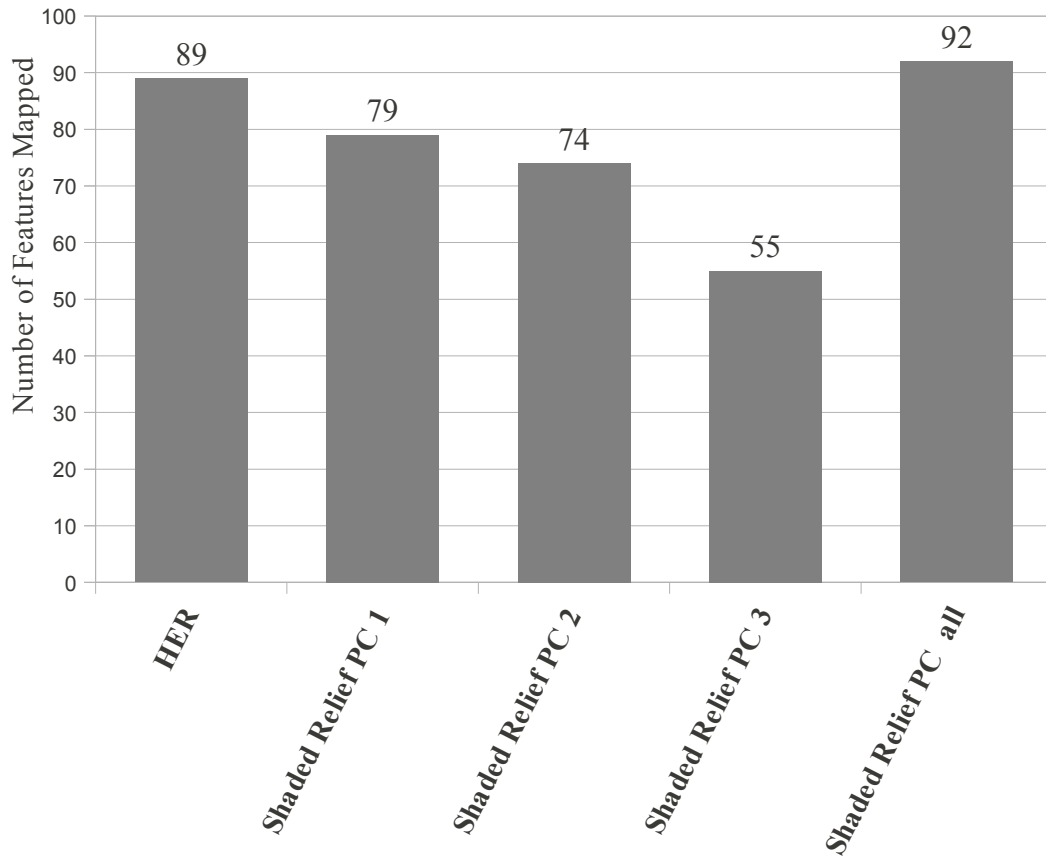


Figure 7.18: Relative feature detection rates from Principle Components Analysis applied to the Airborne Laser Scanned shaded relief model

Transformation	APFL
PC 1	77.86
PC 2	78.71
PC 3	70.98
PC all	80.36

Table 7.21: Average Percentage Feature Recovery in the Principle Components Analysis of the shaded relief images

Table 7.21 shows that the average percentage recovery of features (APFL) mapped by the PCA was quite high especially in the combined data. Friedman's analysis showed that there was no significant difference between PC 1-3 ($\chi^2(2) = 4.98$, $p > 0.05$). Wilcoxon tests showed that there was a significant improvement in the visible length of features to be made by combining the results of PC 1-3 when compared with the results of PC1 alone ($T=0$, $p > 0.01$).

As part of the features mapping process, a series of profiles for each feature was used to aid interpretation from the topographic data. These profiles proved invaluable for identifying the three dimensional aspect of the 2D image on screen and were swifter and more practical to apply than a fly-through type visualisation. However for the shaded relief and PCA of the shaded relief the profiles were difficult to interpret as the elevation data had no logical scale after transformation. Figure 7.19 shows a comparison between the profile of a feature in the PCA analysis, the shaded relief model and original DEM. It can clearly be seen that the shaded relief model of the ALS data (and consequently the PCA transform of shaded relief models) alters the position and profile of the ditch feature at 35m from that recorded in the original terrain model. There is also significant distortion to the shape of the profile that renders the elevation more difficult to interpret archaeologically. Finally, it can be seen that the shaded relief overemphasises a shallow negative feature at 52m and this is also the case in the PCA transformation. As a consequence although archaeological features can be identified using both the shaded relief model and PCA technique, neither are really suitable for accurate location or profile mapping.

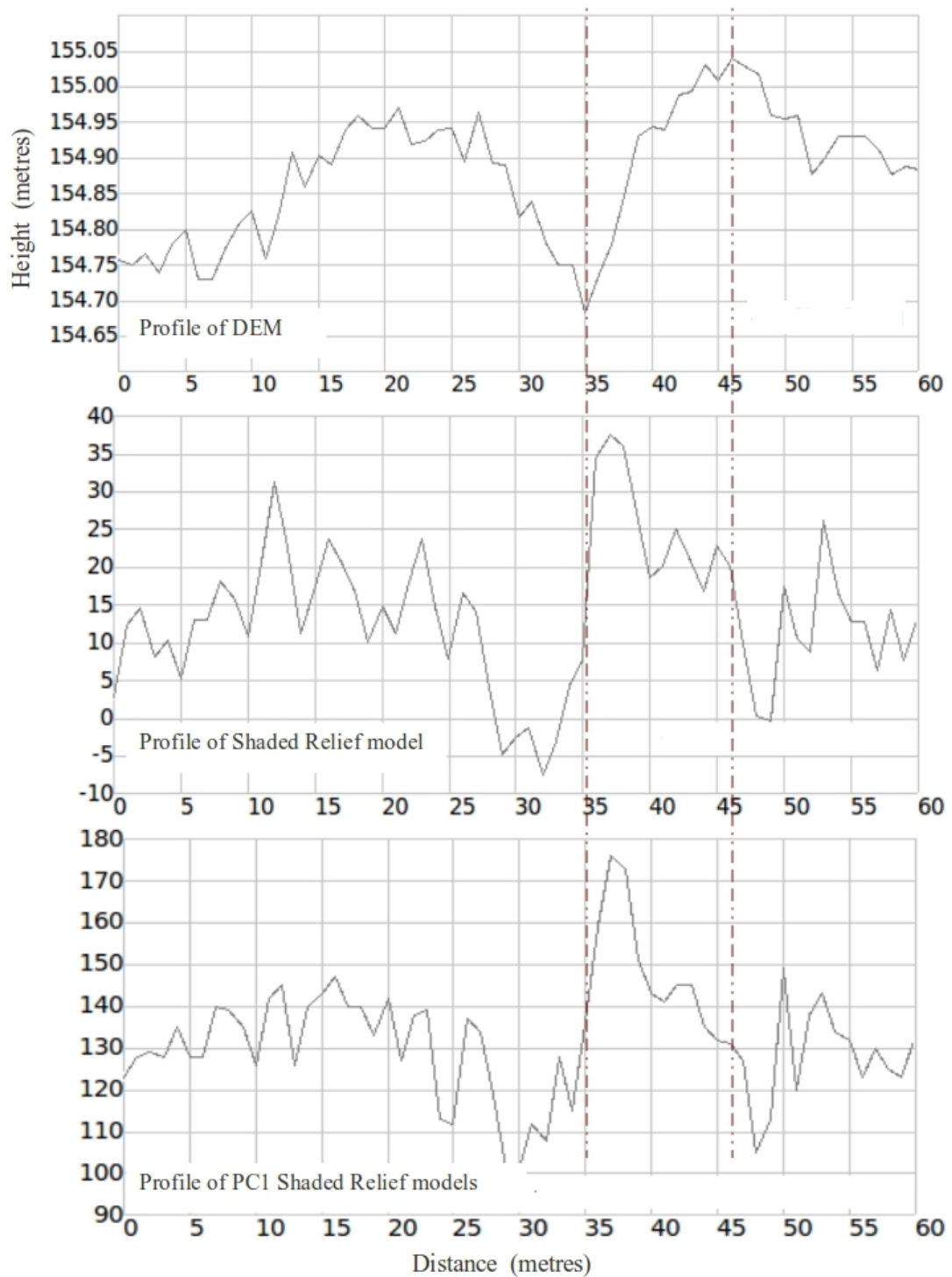


Figure 7.19: Profiles measured for the same transect for the original Digital Elevation Model (DEM), a shaded relief model and the first Principle Component (PC1) of the shaded relief models (with Max and Min values from the Digital Elevation Model highlighted).

7.6.5 Slope, Aspect and Curvature

In the area of subtle topographic features that typified the Everleigh study it was found that only ten features could be detected in the curvature map (figure 7.20). The results of the curvature mapping were deemed unsuitable for identifying archaeological features in this environment therefore only slope and aspect are considered in the results below. These techniques are frequently used in other geographical disciplines for analysing topographic data but neither performed particularly well for mapping archaeological features, with slope recovering 47% of the total number of features visible in the topographic data, and aspect 51% (figure 7.20). For the features that were mapped, however, both slope and aspect mapping had relatively high percentage length recovery rates at 79.5% and 82.5% respectively while curvature performed poorly in comparison with just 45%.

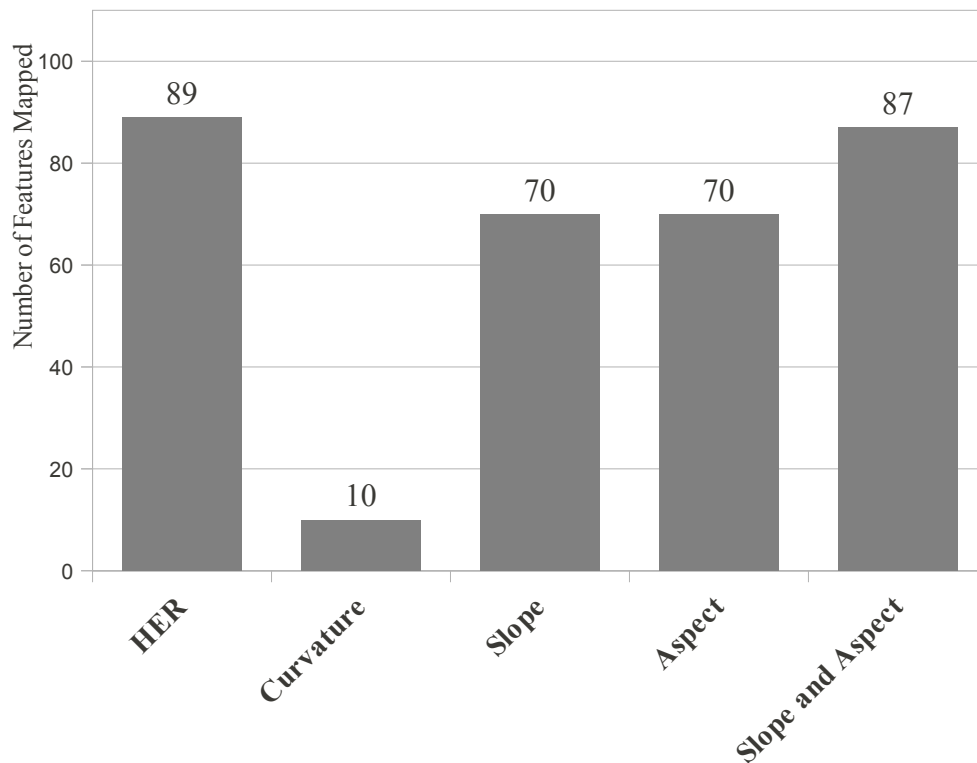


Figure 7.20: Number of archaeological features detected using Slope, Aspect and Curvature mapping

7.6.6 Horizon View

At first view the Horizon View technique appears to provide a sound method of mapping features from the ALS topographic data with recovery rates that compared favourably with the other visualisation techniques (figure 7.21). Table 7.22 shows that the average percentage length recovery is over 80% for all iterations of the technique. The results of the Friedman analysis shows that there is a significant difference in terms of percentage recovery between the iterations ($X^2 = 13.59$, $p > 0.01$), with Wilcoxon test showing that this significant difference was between the 7m /10m and 30m step with performance worsening as the stepsize increased.

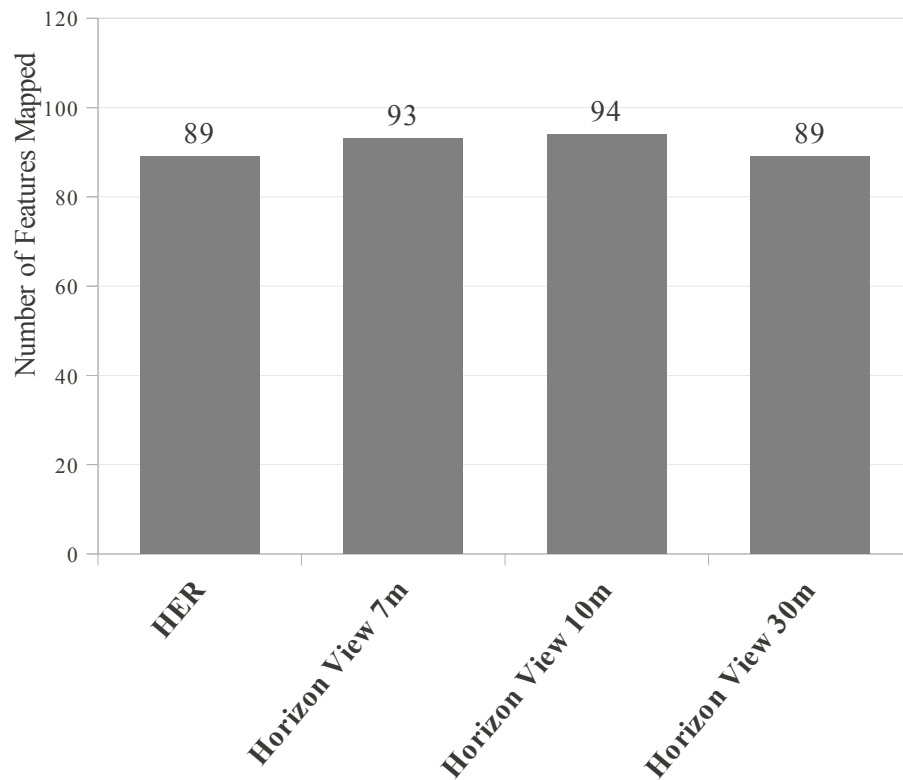


Figure 7.21: Relative feature recovery rates from Horizon View model applied to the Airborne Laser Scanned topographic data.

	APFL
Horizon View 7m	86.62
Horizon View 10m	86.91
Horizon View 30m	81.86

Table 7.22: Average Percentage Feature Length from the Horizon View images

However examining the profiles of features mapped using the Horizon View technique shows two aspects that indicate that this method may have severe limitations for archaeological feature identification. Firstly, the profile of features has no logical scale and is severely distorted and dislocated when compared with the original interpolation. This makes it highly unsuitable for interpretation of the features identified. Secondly, many of the features visible have no representation in the original topographic data. In addition it can be seen that the technique produces many interpolation artefacts that could be mistaken for linear features. Figure 7.22 below, shows an area that appears to be covered in ridge and furrow earthworks on the horizon image but in fact has no trace of any topographical features in the original data. On examining a wider area it becomes clear that the linear features taken to be ridge and furrow are regularly spaced at the same interval as the step size adding further weight to the argument that they are interpolation artefacts (figure 7.23). It is proposed that the high recovery rates are a product of the misinterpretation of this interpolation noise as linear features which dominate in the sample area. Therefore, despite the high recovery rates, the general level of false positives that would occur if this technique were to be used in isolation means it cannot be recommended for archaeological prospection as the only visualisation method.

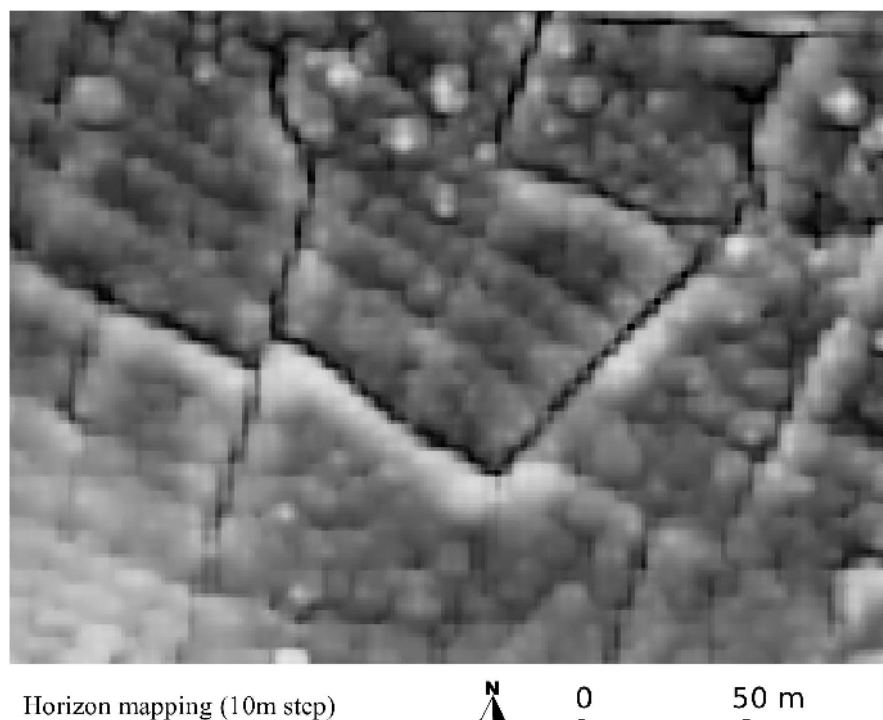


Figure 7.22: Interpolation artefacts in the Horizon View model which resemble ridge and furrow earthworks

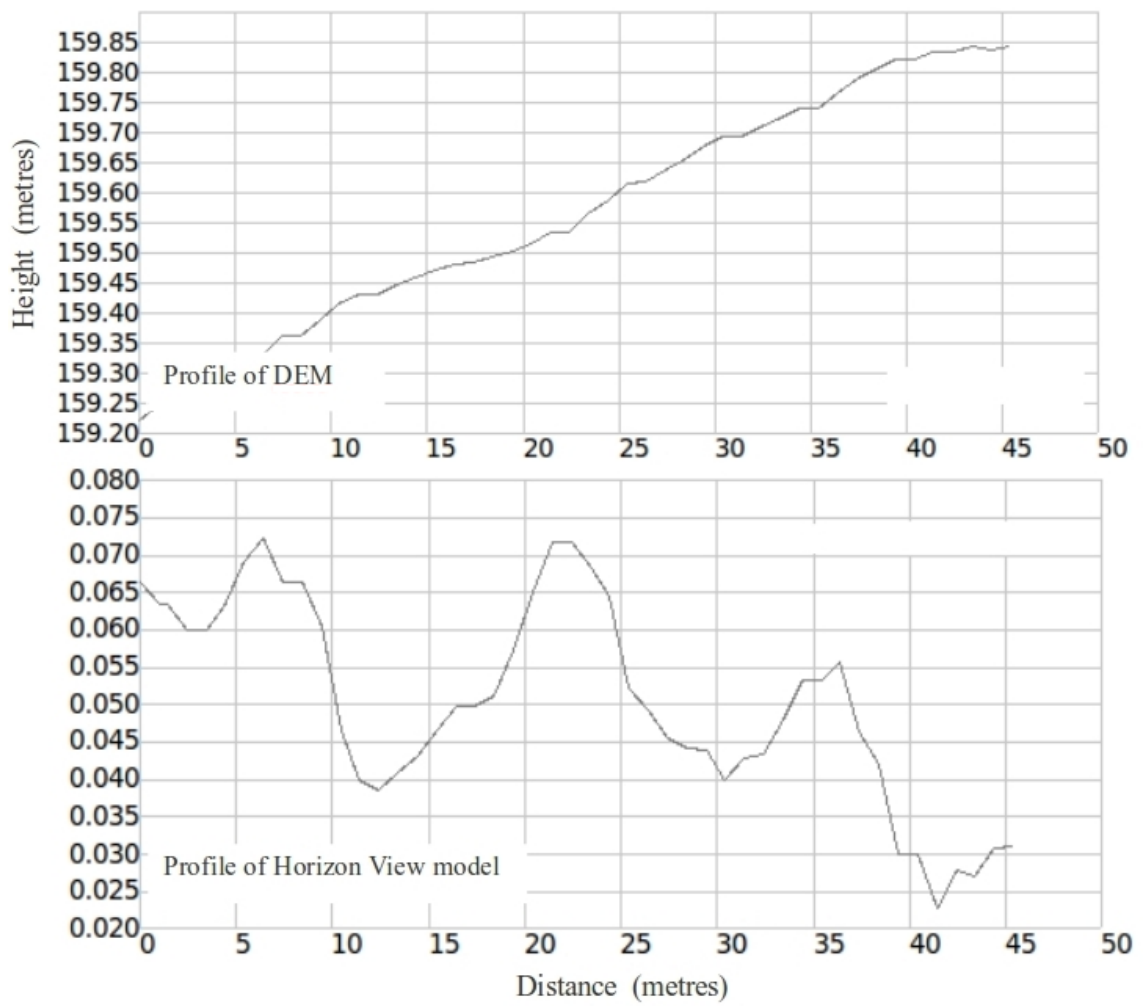


Figure 7.23: The interpolation artefacts in the Horizon View model profile compared with the Digital Elevation Model profile.

7.6.7 Local Relief Modelling

The local relief modelling was conducted using four different smoothing kernel sizes (5m, 7m, 9m and 29m) to examine the impact of this factor on the microtopography and to match to the step sizes of the Horizon View model for comparison. The kernel size should be selected based on the dimensions of the archaeological features expected to be seen given the feature type and source data quality. In the Everleigh landscape it was estimated that a smoothing factor in the range of 5-10m would be most appropriate. The feature recovery rates from the models were surprisingly consistent, and although the most number of features was mapped from the 7m and 9m models there was no significant difference in feature numbers between the different kernel sizes (figure 7.24).

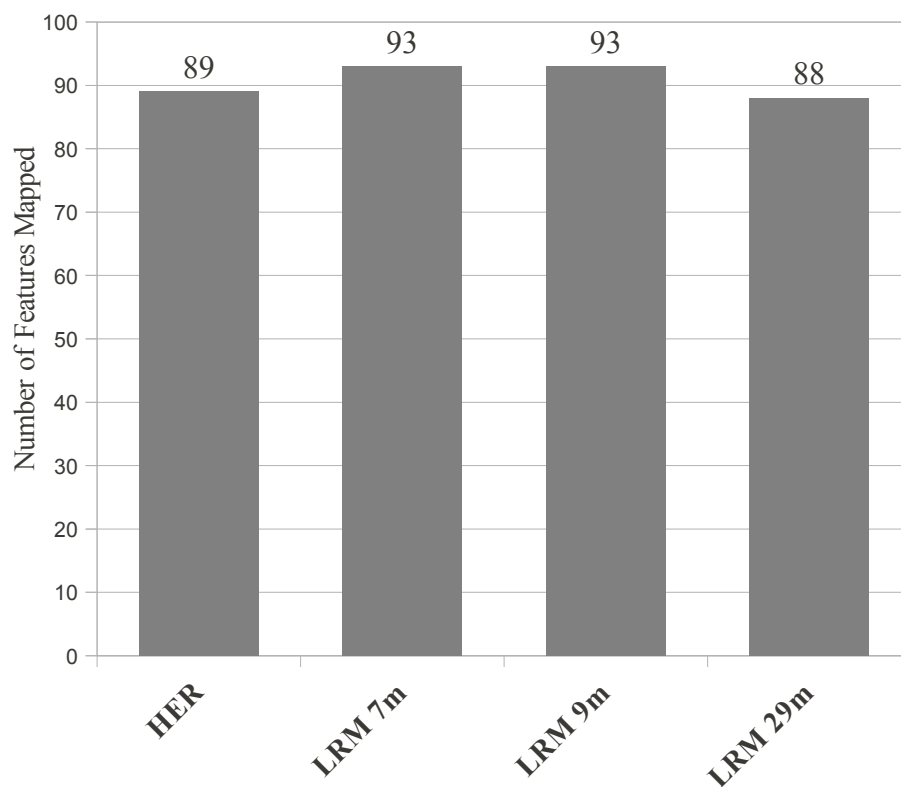


Figure 7.24: Relative feature detection rates from Local Relief Models applied to the Airborne Laser Scan topographic data.

The results of the Friedman analysis show that while the 9m models performed best in terms of percentage feature length recovery, there was no statistically significant difference between the kernel sizes chosen for this area. ($\chi^2(3) = 1.33$, $p > 0.01$).

As with the PCA mapping, profiles of the features were examined to compare the LRM model to the original interpolation. These profiles have a true elevation scale in metres and are often easier to interpret than the original profile as the archaeological topography is clearer once the macrotopography has been removed.

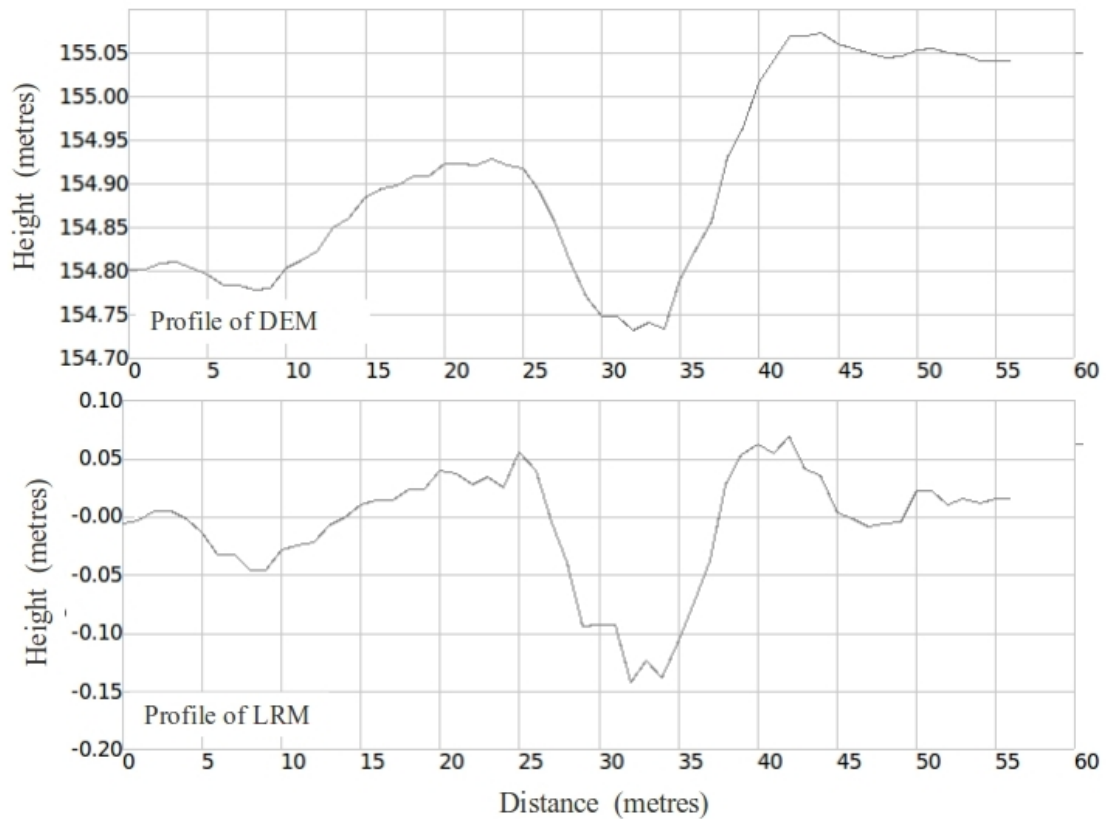


Figure 7.25: Showing the profile of a bank and ditch feature in the original Digital Elevation (DEM) and the Local Relief (LRM) Models

7.6.8 Comparing the ALS Visualisation Techniques

In total 123 or 72%, of the features seen in the Everleigh study area could be mapped to some extent from the ALS elevation data. However each individual technique only recorded 75% or less of the features that could be seen if all the techniques were combined.

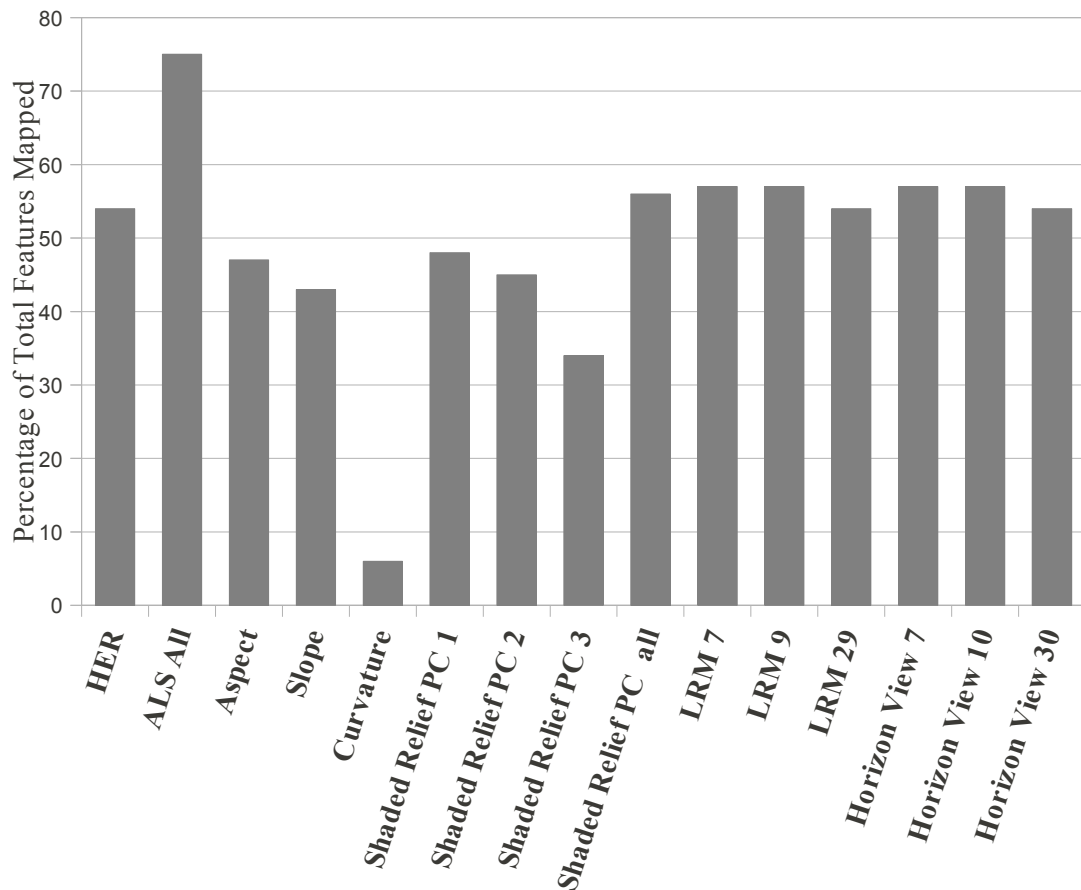


Figure 7.26: Comparison of all Airborne Laser Scan visualisation techniques to the Historic Environment Record record in terms of percentage of total of features detected

For both the LRM and Horizon View the lower resolution models (LRM 29 and Horizon View 30) did not contain data on any features that were not mapped in the high resolution models, and as such have been excluded from this section of the analysis.

Between the Horizon View 7 and 10 there was just one feature that was not recorded by both datasets and this was in Horizon View 10. Therefore the Horizon View 10 was selected as the best technique for comparative analysis.

Between the LRM 7 and LRM 9 there were six features that were only recorded in one of the models (three unique to each). As both techniques also recorded the same number of features neither could be said to be clearly superior therefore both were retained for the comparison.

The results from the different ALS visualisations were analysed for uniqueness to identify complementary techniques. A total of 44 features (36%) were seen in all the visualisation techniques. In all 18 features (15%) were mapped in just one visualisation (table 7.23).

LRM 7 and 9	Lidar PCA all	Horizon View 10	Aspect	Slope
4	2	9	1	2

Table 7.23: Count of features unique to each Airborne Laser Scan visualisation technique

The results of combining two visualisation techniques are ranked in table 7.24. It can be seen that combining any two techniques significantly improves recognition from using any single technique and that the most powerful combination is the LRM and Horizon View. Beyond this, adding the results of a third technique makes a minimal difference to feature recovery as shown in table 7.24.

Visualisation	Number of Features	% Recovery (n=123)
LRM + Horizon View	115	93.50
PCA + Horizon View	114	92.68
LRM + Slope	109	88.62
LRM + Aspect	107	86.99
PCA + Slope	106	86.18
Horizon View + Aspect	105	85.37
Horizon View + Slope	105	85.37
PCA + Aspect	104	84.55
LRM + PCA	101	82.11

Table 7.24: Combination of multiple Airborne Laser Scan visualisation techniques

Visualisations	Number of Features	% Recovery (n=123)
LRM + Horizon + Aspect	119	96.75
LRM + Horizon + Slope	119	96.75
LRM + Horizon + PCA	118	95.93

Table 7.25: Combination of multiple visualisation techniques

7.6.9 Comparing land Use and Visibility in the ALS visualisations

As with the spectral data (section 7.4.3), chi-squared analysis was used to assess the impact of the land use on monument visibility across the ALS visualisation techniques. As before only three of the land use categories were analysed (cultivation to a depth >0.25m, disturbed grassland and minimal cultivation) as the 'undisturbed grassland' category gave expected counts that were too low to be incorporated in the analysis (<5) (section 7.4.3).

Firstly the chi-squared analysis was run on combined results of the mapping exercise for all

ALS techniques. This showed that there was not a significant association between land use and monument visibility across all the features mapped ($\chi^2 = 2.83$, $p < .001$ with a Cramer's V measure of 0.13 indicating that the association was unlikely to have occurred by chance.)

Then the analysis was run for each of the visualisation techniques in turn and the results are summarised in table 7.25. It can be seen that unlike the spectral data, none of the visualisation techniques showed a significant association between land use and feature visibility.

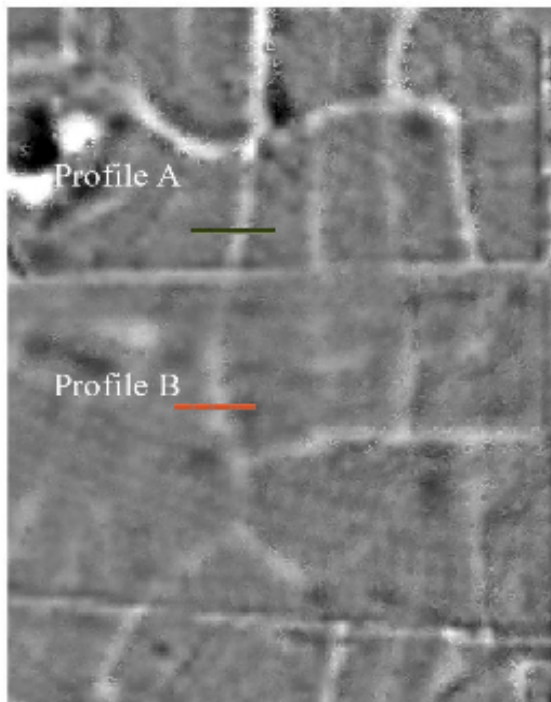
Technique	χ^2	$p < .001$	Cramer's V	Significant association between land use type and visualisation technique?
ALS All	2.83	√	0.13	no
Aspect	0.68	√	0.06	no
Slope	1.24	√	0.09	no
Shaded Relief PC 1	3.13	√	0.14	no
Shaded Relief PC 2	0.6	√	0.06	no
Shaded Relief PC 3	0.3	√	0.04	no
Shaded Relief PC all	5.1	√	0.18	no
LRM 7	5.07	√	0.18	no
LRM 9	4.17	√	0.16	no
LRM 29	2.74	√	0.13	no
Horizon View 7	0.81	√	0.07	no
Horizon View 10	1.44	√	0.09	no
Horizon View 30	3.19	√	0.14	no

Table 7.26: Summary of chi-squared analysis of feature visibility in the ALS visualisations

7.6.10 Assessing Feature Degradation

The Everleigh LRM model also provided an opportunity to quantify the relative degradation of elements of a field system that ran through two land use types; an area of scheduled monument (undisturbed grassland) and a heavily ploughed field to the south (cultivation $>0.25\text{m}$) (Objective 5). While changes relating to damage and degradation can also be seen on aerial photography or spectral data, they can be hard to quantify illustrating the additional value of ALS data.

Profiles of the LRM (which was chosen to reduce the effects of macrotopography), show that the lynchet feature was upstanding to $c.0.15\text{m}$ in the area of scheduled protection and $c.0.05\text{m}$ in the ploughed field (figure 7.27). The feature has also been spread by plough damage from an original width of $c.12\text{m}$ to almost 20m . Without contemporary GCPs these figures can only be a relative indication of damage but provide a useful proof of concept for the LRM model as a tool to assess degradation.



Comparison of lynchet profiles in scheduled and ploughed areas

ALS LRM showing the location of
profiles across a lynchet feature

Figure 7.27: Comparison of Local Relief Model (LRM) profiles for lynchet feature in an area of scheduled monument protection (Profile A) and heavy ploughing (Profile B)

7.7 ALS Data Results (Upavon)

7.7.1 Introduction

Following the visual assessment of the archive data, a planned acquisition of ALS data for Upavon was necessary in order to enable quantitative assessment of the accuracy of the models described in the section above by comparison with ground control points collected via kGPS (Objectives 8 and 9). A further technical aim of the acquisition was to trial the merging of multiple point clouds from the same survey, in order to surpass the limitations of the sensor. With overlying data of varying resolutions from the same acquisition date, the impact of point density (and therefore ALS acquisition strategy) on the topographical accuracy of archaeological features could be assessed (Objective 8).

Additionally the data provided an opportunity for simultaneous collection of geophysical and soil moisture data (Objective 11). The results below focus on the assessment of ALS accuracy, the correlation of ALS data and ground observations is detailed in the next chapter (section 8.3).

7.7.2 ALS Resolution and Accuracy

The resolution of the “low” and “high” ALS point cloud (as defined by the acquisition parameters, section 5.3.1) were analysed using OPALS to calculate the statistics for individual flightlines (to exclude areas of overlap) and across the whole data set. As can be seen from table 7.27 the difference in terms of points per metre² between the high resolution flight was less than one point per metre. This confirms that with improved sensor specification, the compromise between ALS resolution and optimal hyperspectral data collection no longer compromises the quality of ALS data to the same extent.

		Average points per metre squared (last pulse)
Single flightlines	“Low” resolution	3.67
	“High” Resolution	4.02
Combined Point Cloud (1km sample)	“Low” resolution	4.43
	“High” Resolution (Area 2)	10.34
Area Average	All (Area 1)	6.18

Table 7.27: Summary of the resolution of the bespoke Airborne Laser Scan data, Upavon Study Area

This meant that after filtering, the point cloud could comfortably be rasterised to a 0.5m raster for the whole study area and a 0.25m resolution for the high resolution area. The rasterised ALS data were compared with the GCP data, giving an RMSE of 0.09m across the Upavon area for the lidar model.

7.7.3 Assessing the Accuracy of the Archaeological Feature Buffering

The accuracy of the method of defining archaeological features from the HER record by buffered polylines (such as is required for the application of the separation index, section 6.10.1) was assessed using the 0.25m resolution LRM of the area. By altering the buffer width it was possible to see the impact of the mapping method on whether archaeological features could be defined statistically as positive or negative from the LRM. As can be seen from table 7.28, there was no significant difference in the mean elevation values of the archaeological features recorded in the study area, however as shown in figure 7.28 the histogram and therefore the statistical separability of positive and negative features is affected by buffer size with the 0.5m buffer providing the best separation.

Buffer Size	Basic Statistics	Positive Features	Negative Features
2m	Min	-0.46	-0.41
	Max	1.61	3.86
	Mean	-0.03	0.03
	Stdev	0.05	0.09
1m	Min	-0.46	-0.38
	Max	0.21	3.86
	Mean	-0.03	0.03
	Stdev	0.05	0.08
0.5m	Min	-0.46	-0.36
	Max	0.19	3.80
	Mean	-0.04	0.03
	Stdev	0.05	0.08

Table 7.28: Statistical summary of the planned ALS data, Upavon

Analysis such as this also helps to assess the potential for using the LRM as a basis for automatic feature detection. Figure 7.28 shows that digitisations that are visually perceived as a positive or negative features from aerial photography may not be statistically separable at the grid cell level.

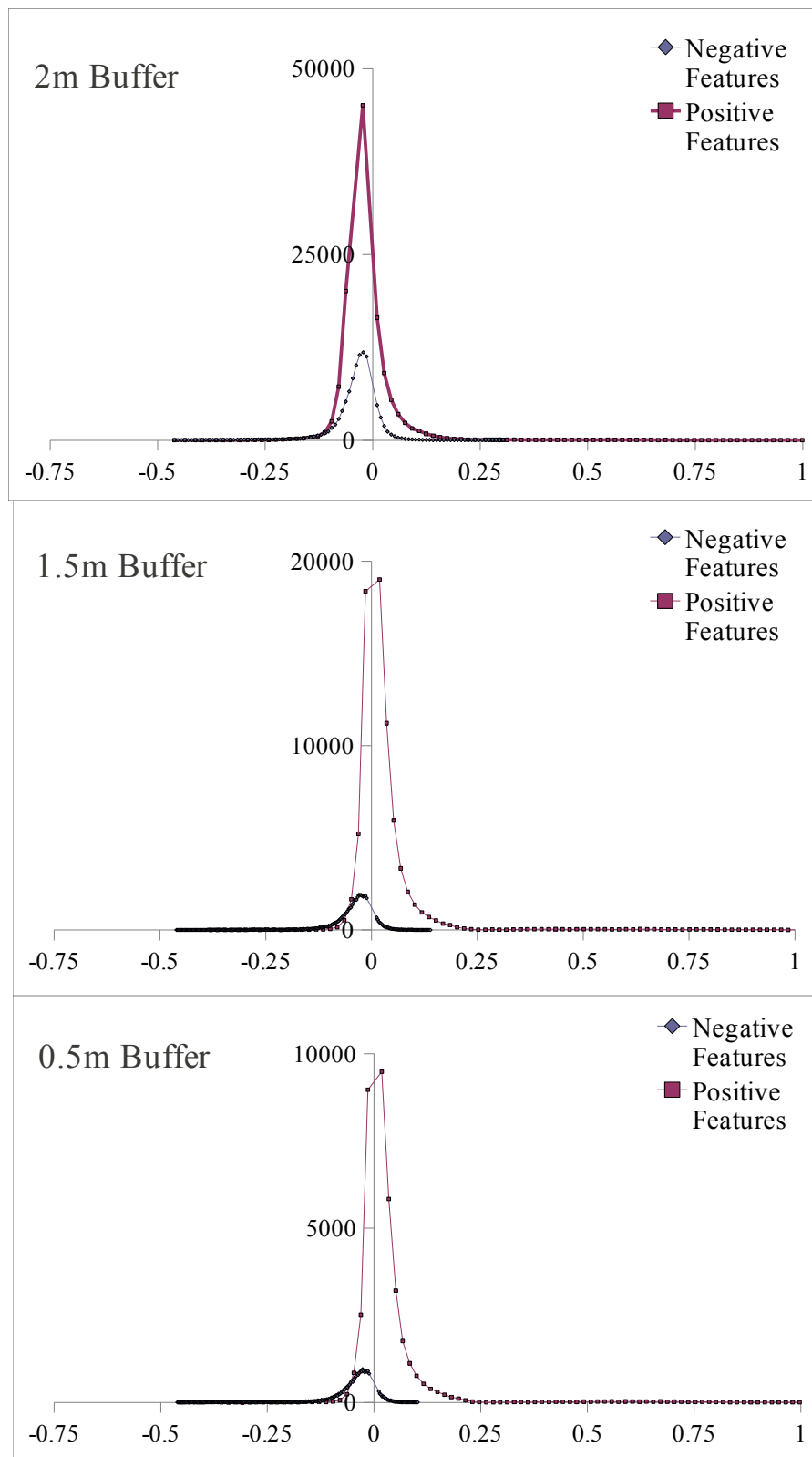


Figure 7.28: Comparison of Local Relief Model histograms for positive and negative features (as defined from the Historic Environment Record)

7.7.4 Assessing the Accuracy of the LRM Model

The results of the slope analysis for the LRM model described in section 6.10.2 are illustrated in Figure 7.29. The results show that the slope measures along the profile for the DTM and GCP are broadly the same with an RMSE of 1.21° . However the microtopography shown in the model clearly deviates substantially from the DTM and GCP data with an RMSE of 1.99° across the profile (table 7.28).

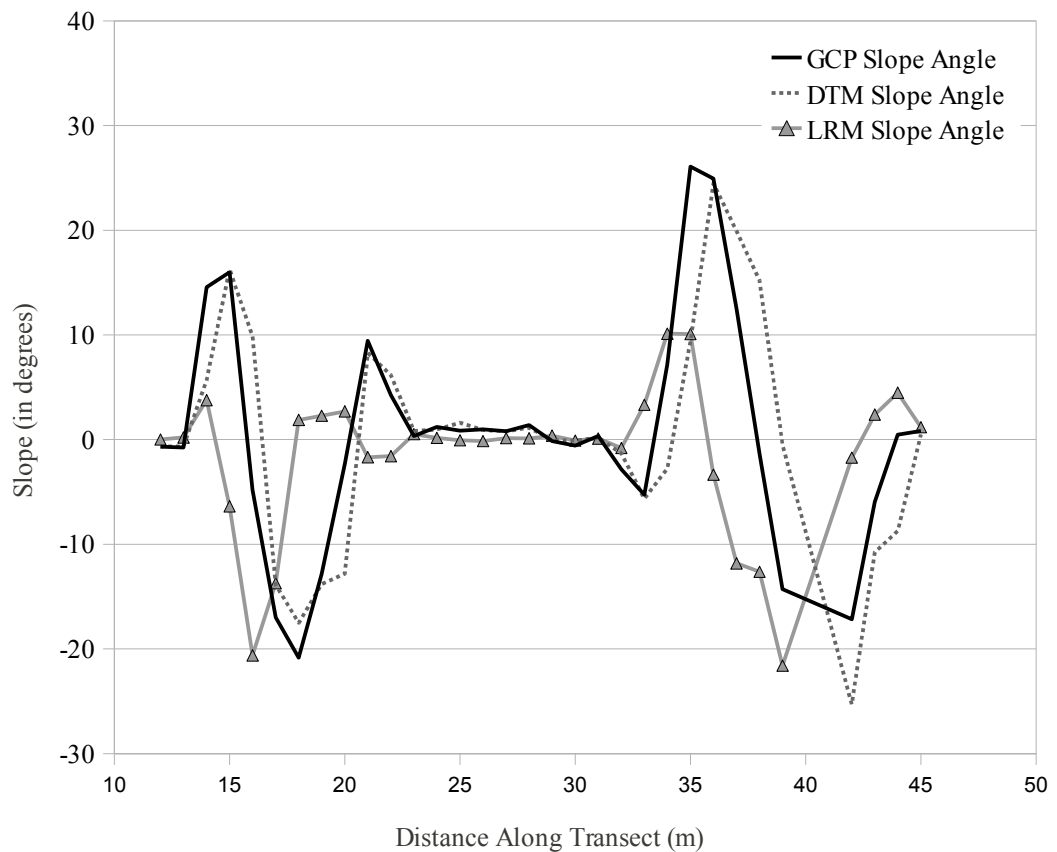


Figure 7.29: Comparison of slope from the Ground Control Point (GCP) data, Digital Terrain Model (DTM) and Local Relief Model (LRM)

To assess the RMSE over the bank and ditch features alone, these were separated from the points with no change in slope (table 7.29). It can be seen that the RMSE for areas of flat topography is low, indicating that the LRM is accurately defining areas with no change in slope, but in areas of microtopography the RMSE of the LRM is higher than that of the original DTM. The assessment of slope helps to quantify the accuracy of the LRM's depiction of microtopography in profile, indicating that it could be 169% different to GCP measurements.

	RMSE (°)		
	0 Slope	Microtopography	Whole Profile
GCP – DTM	0.84	1.88	1.21
GCP – LRM	0.42	3.17	1.99
DTM – LRM	1.22	4.46	2.55

Table 7.29: Root Mean Square Error (RMSE) between Airborne Laser Scanned models and Ground Control Point data

Perhaps the most interesting result is that the LRM is closer to the values of slope of the GCP data (RMSE 3.17°) than it is to the DTM from which it was derived (RMSE 4.46°). This means that the error of the DTM-LRM cannot be used as a proxy measure for the accuracy of the LRM compared with the GCP.

7.7.5 Summary

This chapter has covered the results of the individual analysis of the two key data types used in this research, digital spectral data and ALS. The analysis has covered both archive ARS data for the Everleigh study area and planned acquisition of data for the Upavon study area. The next chapter covers the integration of different ARS data along with ground-based measurements and concludes with a summary linking the results presented in both chapters with the objectives of the research (section 8.10).

8 Results – Integrated Datasets

8.1 Introduction

This chapter presents the results of the integration of data from multiple sources along with quantitative comparison of all ARS techniques for the Everleigh Study Area.

First, the results of the methods trialled for digital combination of the archive ARS data for the Everleigh area are given in section 8.2 directly contributing to Objective 12. Secondly, for the provision of background data in support of the ARS surveys (Objective 11), section 8.4 presents the results from the assessment of archive weather data for both study areas. Following on from this are the results of the geophysical survey (8.5) and other ground-based observations (6.14) which are applicable to the Upavon study area. Section 8.7 then gives the results of the correlation analysis between ground observations and ARS data.

The latter sections contain the quantitative comparison of ARS data that contribute to Objectives 3 and 4. Section 8.8 gives the results of the comparisons between different ARS data sources with comparisons based on feature number, feature type and average percentage feature length recovery. Section 8.9 gives a detailed comparison of “traditional” and “new” techniques for visualisation of ARS data based on the archaeological feature mapping from the Everleigh archive data.

The final section of this chapter (8.10) provides the summary of the results presented in Chapters 7 and 8 in relation to the objectives outlined in Chapter 3.

Combining Data from Multiple Sensors

8.2 Digital Data Combination

8.2.1 Introduction

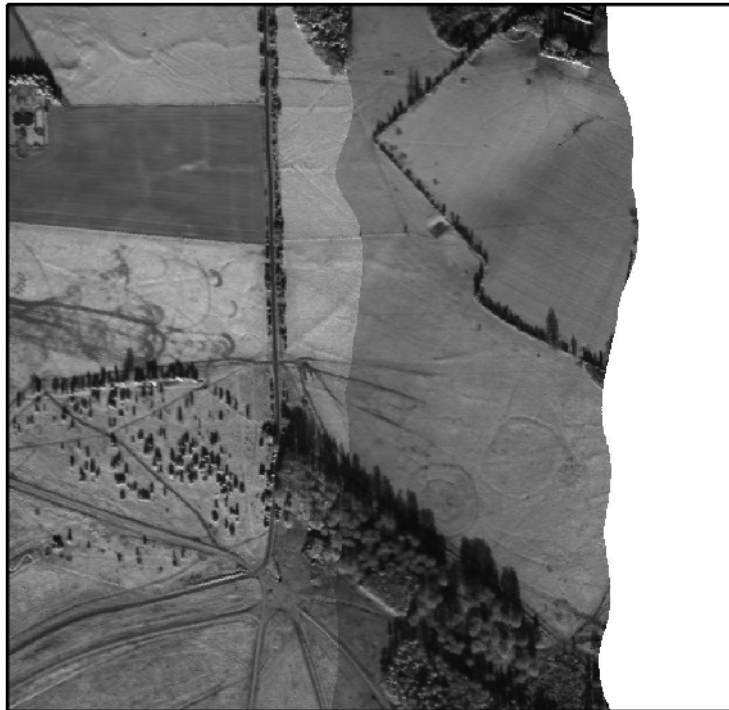
The digital combination of multiple datasets was undertaken in fulfilment of Objective 12. The best performing spectral and ALS visualisation from the Everleigh Archive dataset were selected for integration

8.2.2 Raster Mathematics

The results of the first techniques trialled to combine the information in the spectral and topographic data sets were disappointing. The combination of the January 14-band PC1 and the scaled DEM did not allow for the detection of any features that could not be seen in the spectral data alone (figure 8.1).

The same technique was trialled using the LRM topographic model (9m kernel) and the January 14 band PC1. Using this topographic model improved the visibility of features compared with each of the contributing sources as shown in figure 8.2. The maximum number of features expected was 120, based on the addition of features mapped from the source spectral and topographic data separately (minus the number of features that were visible in both), giving a recovery rate of 81% for this technique. The technique also gave an improvement in APFL from that recorded by the PC1 of the spectral data (81.0% vs. 72.6%) bringing it to the level of the the LRM 9 model (81.0%).

This result shows that the LRM is better suited than the DEM for combining with other datasets as the microtopography is not masked by larger changes in elevation.



January Spectral Data PC1



January PC1 combined with the DEM



0

500 m

Figure 8.1: The result of combining the Principle Component 1 of the January spectral data with the Digital Elevation Model

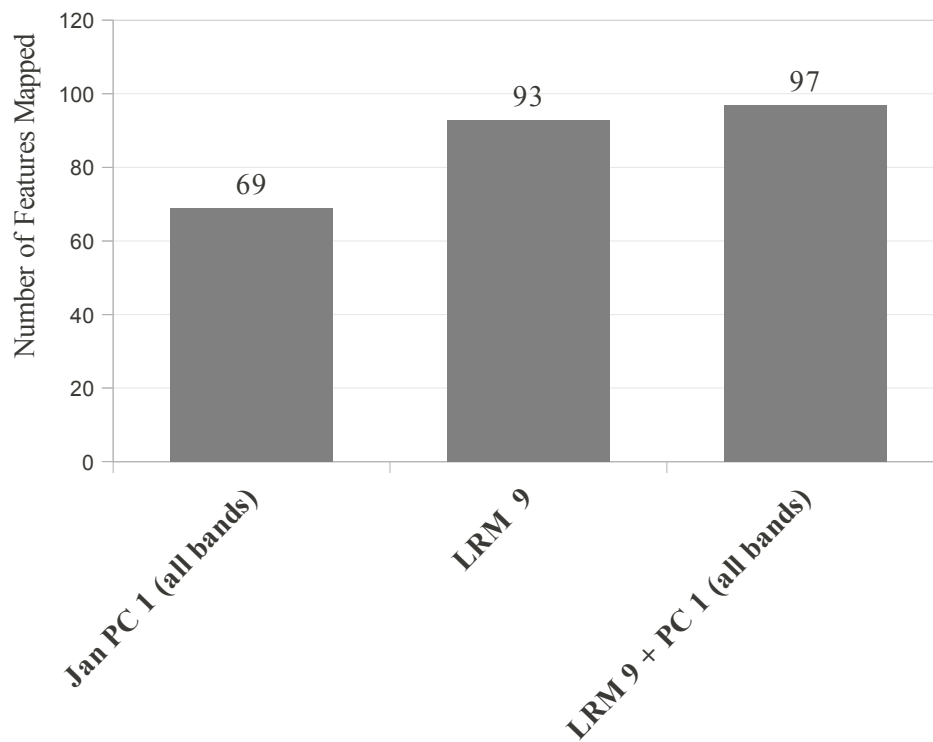


Figure 8.2: Feature visibility in the digitally combined LRM 9 and January PCI raster compared with the contributing sources.

8.2.3 Brovey Transformation

The Brovey transformation was trialled using the FCC of the January data as the red, green and blue bands and an alternative to simple addition of multiple rasters. The varying success resulting from the incorporation of the scaled DEM, LRM 9 model and the Horizon View 10m models is illustrated in figure 8.3. The comparison shows that only the Brovey sharpening using the LRM 9 topographic layer exceeded the number of features mapped by any individual source used for the composite (figure 8.3). The results were further analysed by calculating a prediction of the maximum number of features (topographic plus spectral minus the number mapped by both) and comparing the number of features visible in the Brovey transformation to this prediction (table 8.1). The results show that the use of the scaled DEM and LRM 9 models as the topographic layer of the transform gave approximately 80% of the expected maximum number of features. The Horizon 10 model performed noticeably worse than this with a 66% recovery rate.

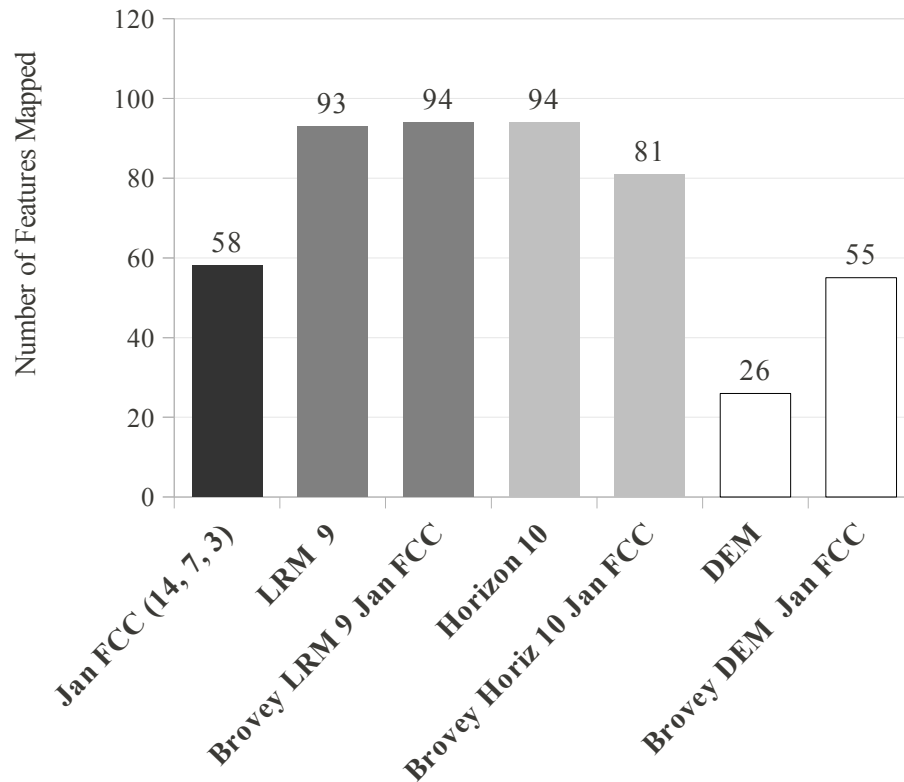


Figure 8.3: Comparison of all Brovey transformations of the January spectral False Colour Composite bands 14, 7 and 3

Topographic Layer	Topographic Feature Total	Jan FCC Feature Total	Features seen in both Spectral and Topographic Data	Predicted Brovey Total Features	Actual Brovey Feature Total	% Recovery
DEM	26	58	14	70	55	78.57
LRM 9 total	93	58	34	117	94	80.34
Horizon 10	94	58	30	122	81	66.34

Table 8.1: Table showing percentage recovery of predicted features from the Brovey transformations of the January False Colour Composite data

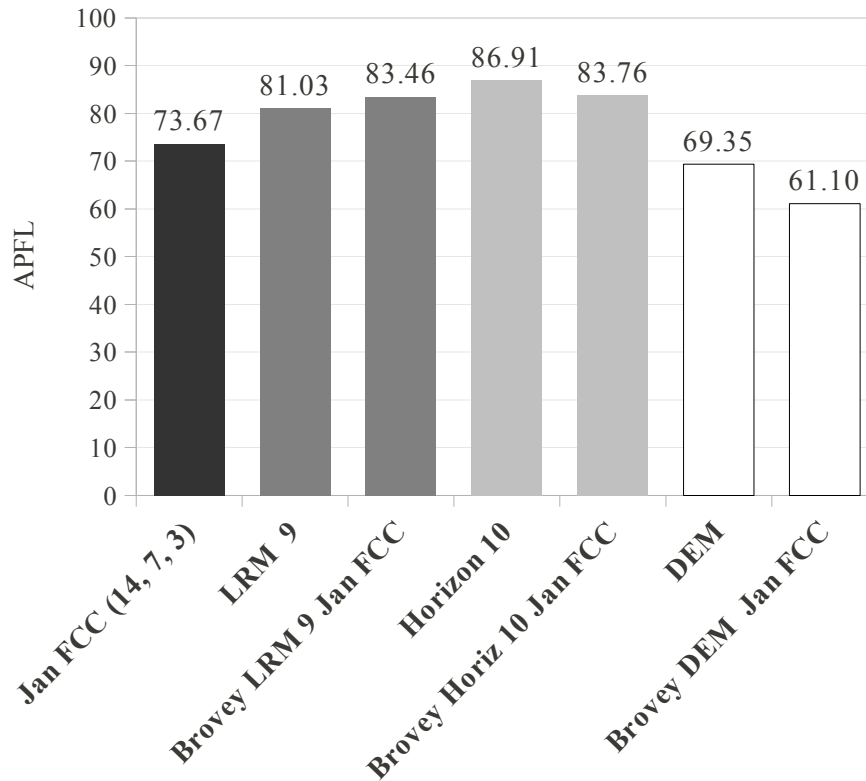


Figure 8.4: Comparison of Average Percentage Feature Length for all Brovey transformations of the January spectral False Colour Composite bands 14, 7 and 3

Figure 8.4 shows that only the Brovey sharpening using the LRM 9 topographic layer exceeded APFL recovery achieved by both the individual sources used for the composite. The average recovery from the Horizon View Brovey transformation provides an improvement on the FCC average percentage recovery but a reduction from that of the Horizon View model alone. It is considered however following the analysis presented in section 7.6.6, that the utility of the Horizon View model may be undermined by the detection of false positives and so cannot be considered a suitable topographic model for the Brovey sharpening method.

As the use of the LRM model in the Brovey sharpening appeared to offer the best results for the January spectral data the technique was also trialled with the May FCC. Table 8.2 indicates that the combination of the LRM and May FCC data allowed the mapping of almost 88% of the features mapped from each contributing source, while figure 8.5 shows that the Brovey transformation also provided an improvement on the average feature length recovered.

LRM 9 total	May FCC (12,7,3) Feature Total	Features in LRM 9 and May FCC	Predicted Brovey Total Features	Actual Brovey Feature Total	% Recovery
93	53	32	114	100	87.72

Table 8.2: Table showing percentage recovery of predicted features from the Brovey transformations of the May False Colour Composite data

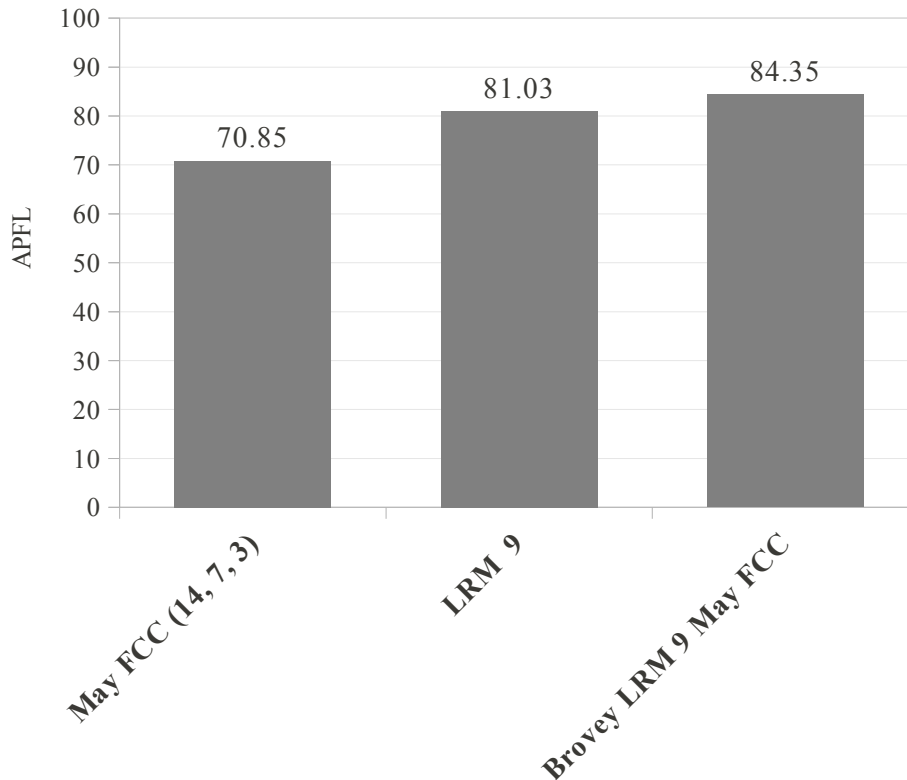


Figure 8.5: Chart comparing Average Percentage Feature Length for the Brovey transformations of the May False Colour Composite data

In conclusion, while the Brovey transformation cannot replicate the optimum visibility of features mapped from the contributing sources in terms of number of features, recovery levels were shown to be more than 80%, or four in five features when the LRM 9 model was used as a topographic base for the January spectral data, with this figure rising to almost nine in ten for the May spectral data. The fact that the Brovey transform was also shown to improve the percentage of feature length mapped compared with either of the contributing sources indicates that it may have potential as a visualisation technique for combining three bands of spectral data with the LRM topographic model.

Integrating Ground Based Data

8.3 Introduction

This section gives the results of the ancillary data processing necessary to investigate the wider environmental conditions affecting the detectability of archaeological features in the ARS data (Objectives 4 and 11). Archive weather data was collated for both the Everleigh and Upavon study areas. The opportunity for soil, spectral and geophysical measurements was only possible due to the nature of the ARS collection for the Upavon Study Area which allowed ground observations to be planned to coincide with airborne data collection. Data collection focused on soil moisture via direct measurements and the proxy measurement of earth resistance survey as these measures are most sensitive to change over time. The results of this ground-based data collection is given in sections 8.4-8.6

The analysis of ancillary data indicated that differential soil moisture may be a significant contributing factor to archaeological feature visibility within spectral data. Further work to understand the correlation between the ARS and ground-based data is reported in section 8.8.

8.4 Archive Weather Data (Everleigh and Upavon)

8.4.1 Average Rainfall

The average rainfall measures among the five closest weather stations (figure 6.9) for the 14 days before data acquisition for each of the datasets are plotted in figure 8.6. It can be seen that the two hyperspectral datasets for which the archaeological visibility (Jan 2001 and March 2010) was deemed to be best were collected following a period of 2-3 days of zero rainfall, while the data collection in May 2001 was preceded by three days of rainfall. There was no recorded rainfall on the day of any of the data acquisitions.

Although the nearest weather stations lie between 7km and 15km from the study area, these can be seen to be broadly representative of rainfall figures in the area. An average daily difference between the stations of 4.2mm was recorded in January 2001, 0.37mm in May 2001 and 1.32mm in March 2010.

Although there is a lack of contemporary ground observation data for the field sites, rainfall could be seen as indicative of general soil moisture levels. However a larger sample size would be required to test the hypothesis that ground moisture contributes to archaeological feature visibility.

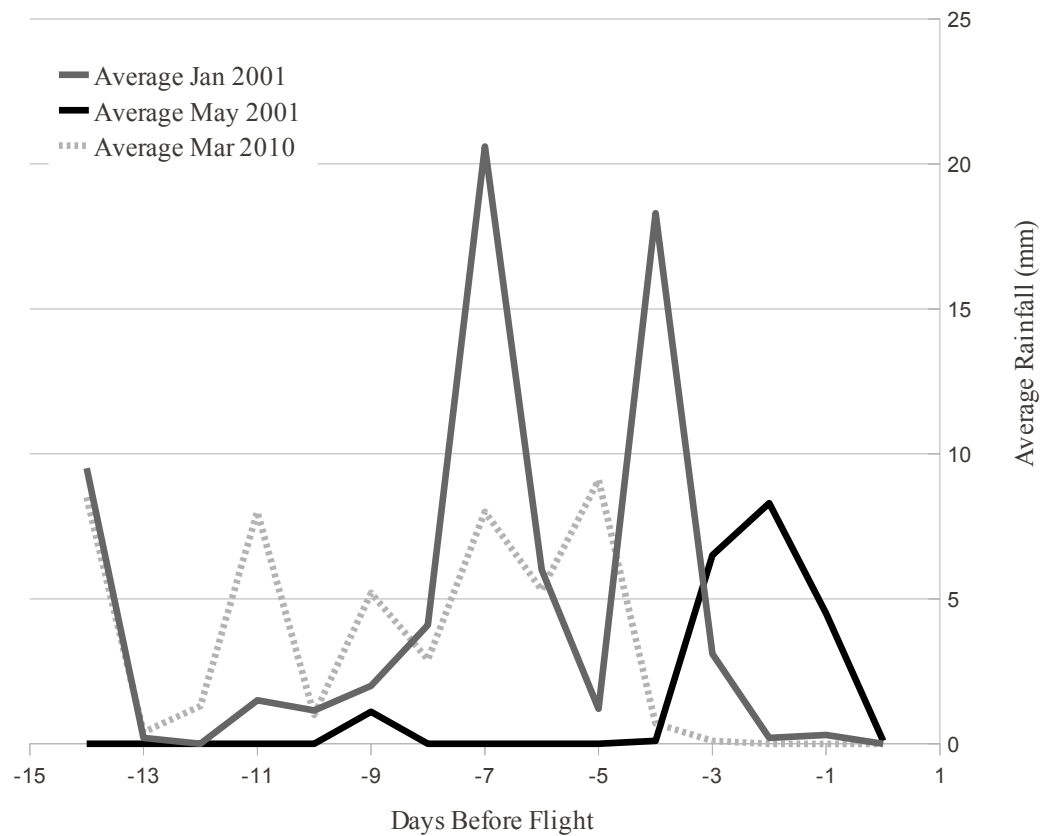


Figure 8.6: Average rainfall for the Salisbury Plain area

8.4.2 Soil Moisture Deficit

Soil moisture deficit (SMD) information was only available from the Environment Agency for the March 2010 flight. The SMD for EA's South and South Western regions¹⁰ was zero, meaning that the soil was at its moisture capacity at this time. It was not felt that this measure, which is generalised across time, location, geology and environment was a suitable indicator of local ground conditions. Unfortunately no more specific data were available regarding SMD.

¹⁰ Salisbury Plain straddles the boundary of these two regions

8.5 Geophysical Survey (Upavon)

The results of the geophysical surveys are presented here with respect to their application for combination with the ARS data. The full interpretation of the geophysical surveys can be found in Appendix 2. Figure 8.7 below gives the relative location of the geophysical data figures in this section.

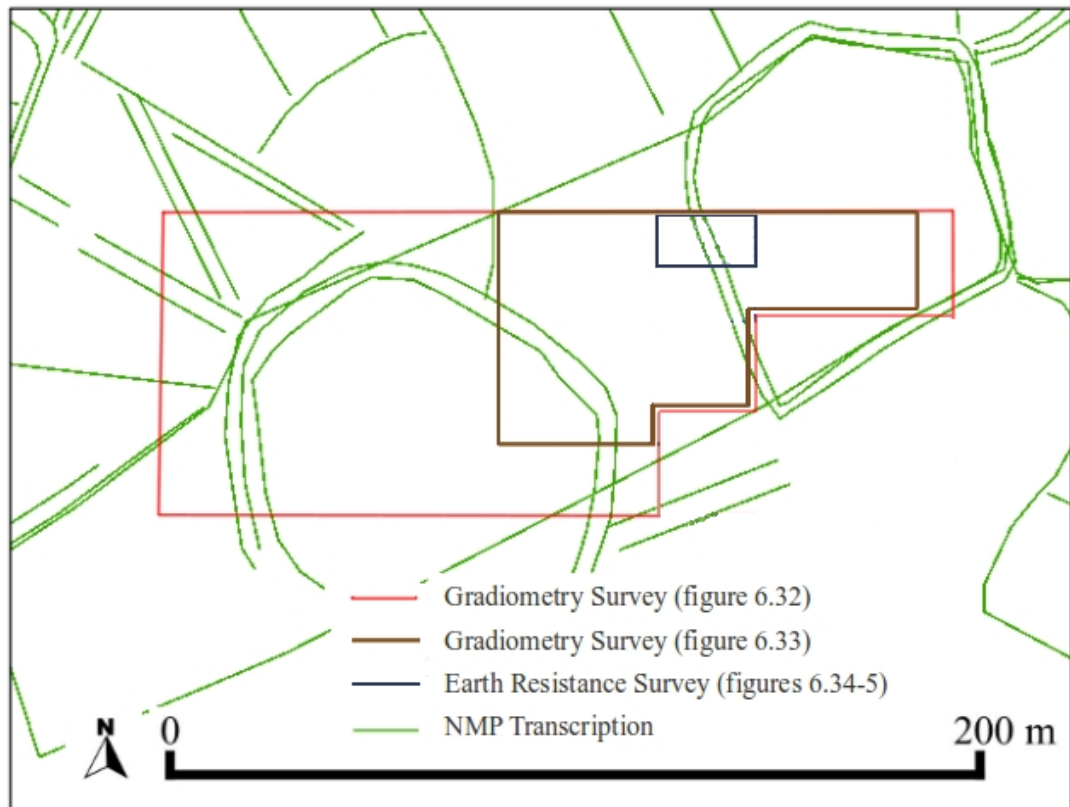


Figure 8.7: Relative location of geophysical survey data (figures 8.8-8.11)

8.5.1 Gradiometry Survey

The survey showed the location of the enclosure at Upavon Field Site 1, Coombe Down Enclosures (figure 8.8). The bank feature selected for resistance survey was very subtle in the data and can best be seen in profile (figure 8.9). The results of the gradiometry survey allowed the geometric correction of the aerial photography (NMP) transcription recorded in the HER to enable accurate placement of the subsequent earth resistance, GPR and soil moisture surveys.

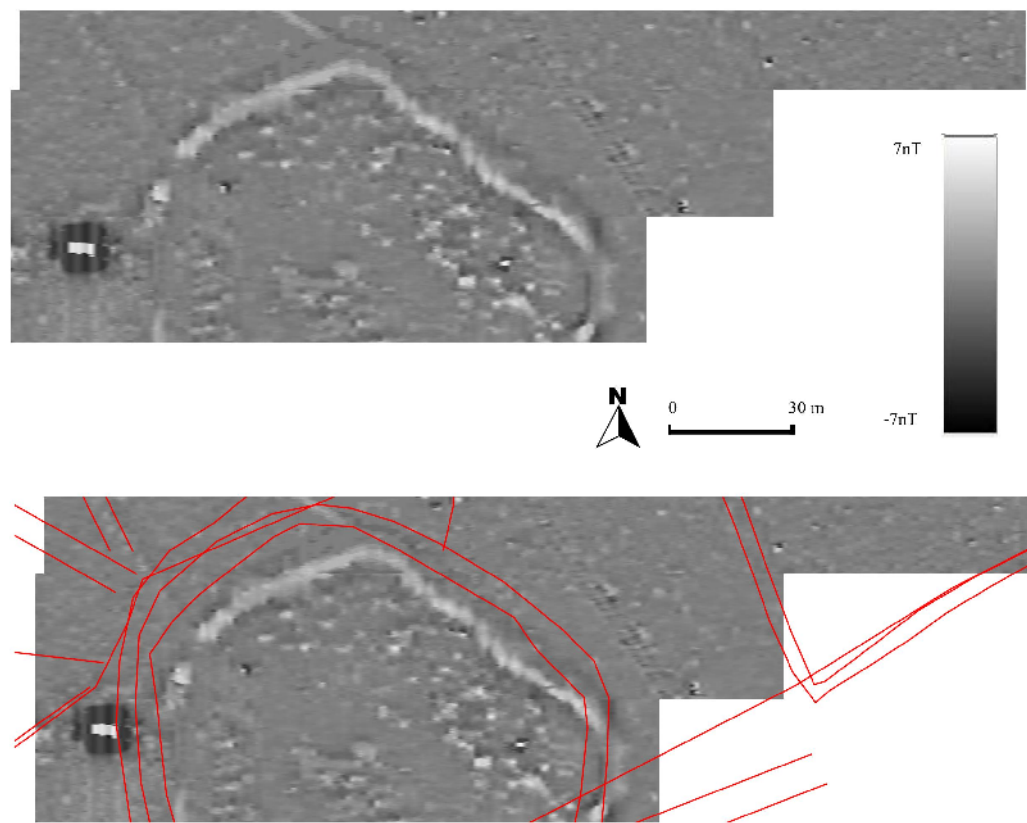


Figure 8.8: Gradiometry survey of Upavon Field Site 1 (SU 177 522) overlaid with the Wiltshire Historic Environment Record

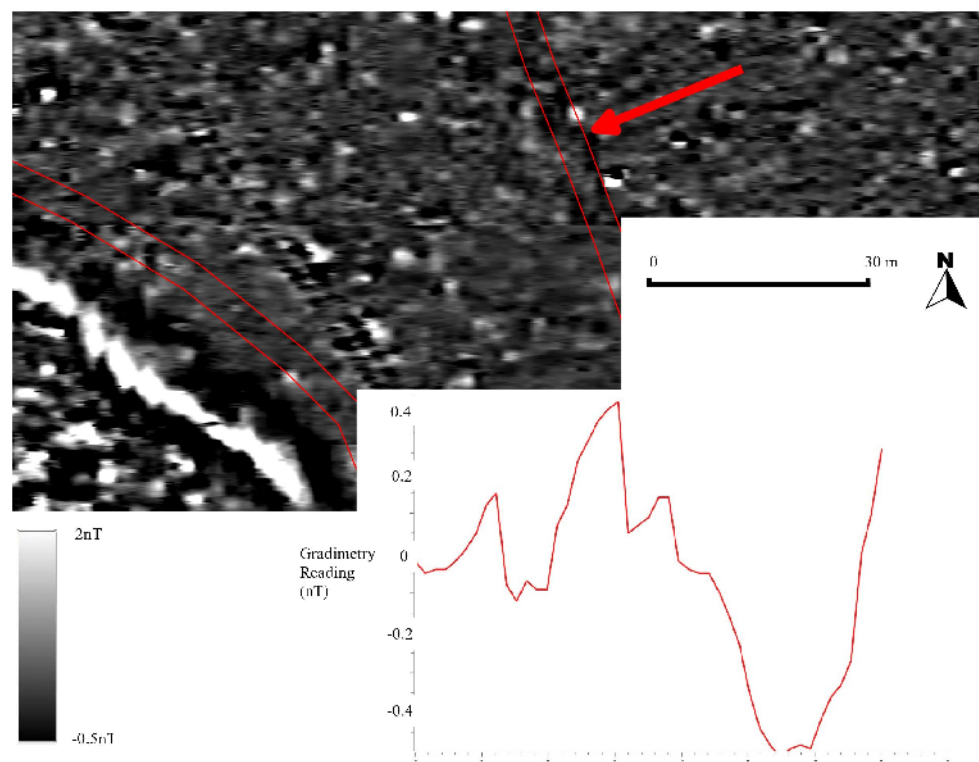


Figure 8.9: Detail of eastern enclosure bank (SU 177 522 Upavon Field Site 1) in gradiometry data with profile

8.5.2 Earth Resistance Survey

The earth resistance transect was able to detect the bank feature in the 0.25m probe separation data (figure 8.10). This showed that the structure of the bank was altering the earth resistance properties in the first 0.25m of the soil column and also that the bank was approximately twice as wide (~10m) as had been recorded from aerial photographs (~5m).

The bank feature could not be as clearly discerned in the 0.5m probe separation data (figure 8.11). From comparison with the auger survey results (section 8.6), it is likely that the depth of this survey was recording the resistance of the chalk bedrock below the feature.

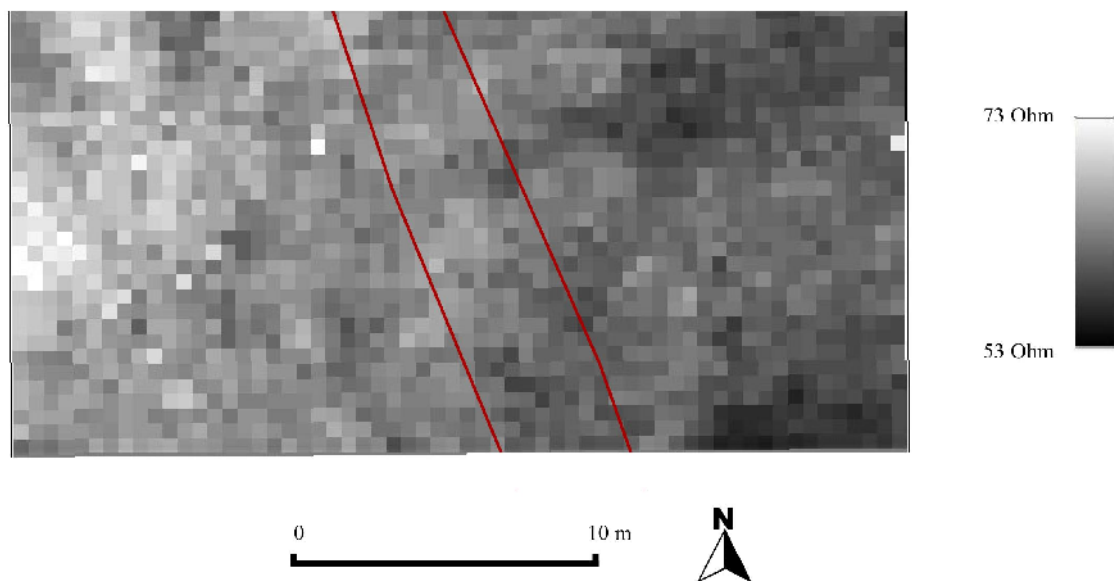


Figure 8.10: The high resistance bank feature as shown in the 0.25m apparent resistivity survey (overlain with the Wiltshire Historic Environment Record)

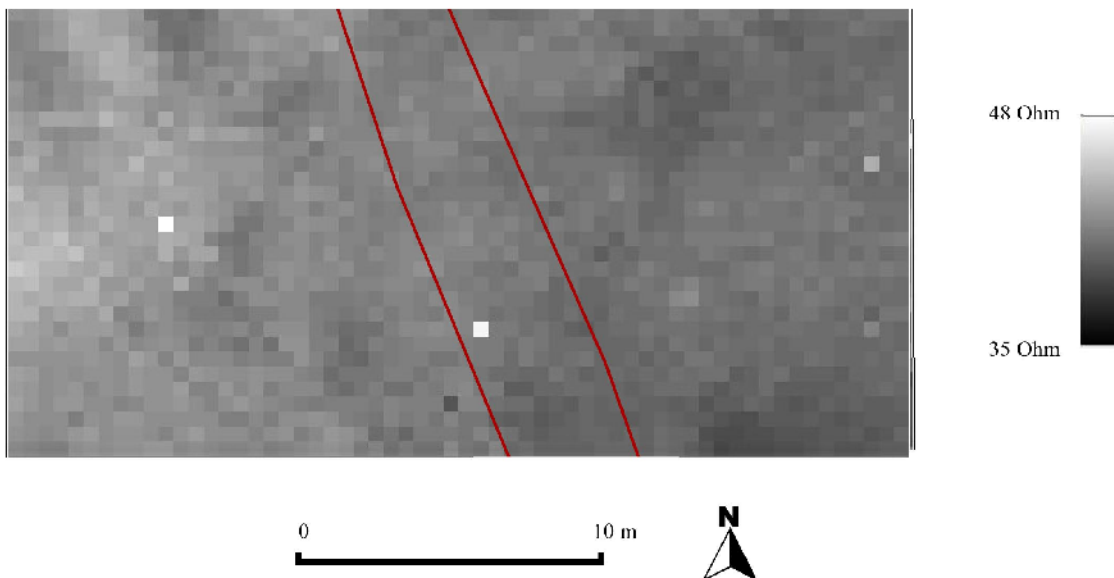


Figure 8.11: The 0.5m apparent resistivity survey (overlain with the Wiltshire Historic Environment Record)

8.6 Soil Sampling

Due to limited time on site it was only possible to take six moisture cores on the day of the ARSF flight, of these two (A and F) were to a depth of 0.1m and four (B-E) sampled to a depth of 0.2m (table 8.3). The cores were taken across the known bank feature at SU 177 522 (Upavon Field Site 1, figure 8.12). It is recognised that the small number of samples, limited geographical coverage and the random strategy with which they were collected are all factors that limit the level of interpretation that can be made from these data, however as this experiment represents the first attempt at simultaneous ground based soil moisture data capture for any ARS project it has been retained here for reference and will be fully evaluated in section 8.6.

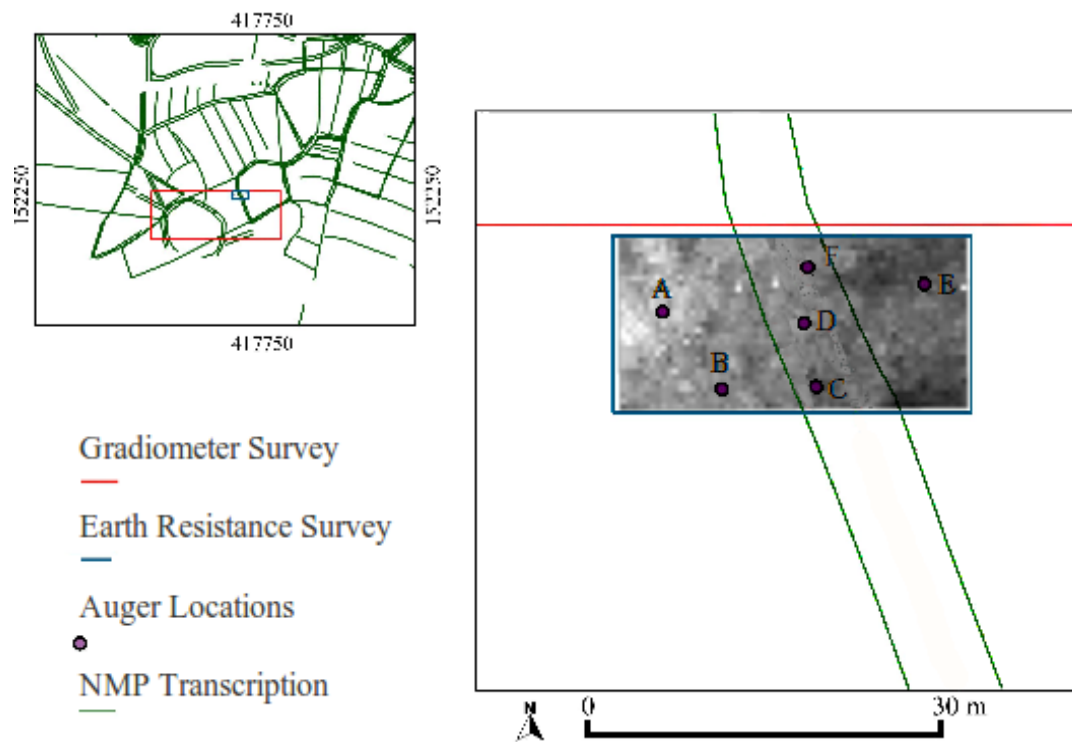


Figure 8.12: Location of soil moisture samples, Upavon Field Site 1, overlain on the 0.25m apparent resistivity survey

Core	Category	water content as % of dried weight	
		0-0.1m	0.1-0.2m
A	background	19.38	
B	background	20.91	17.71
C	bank	19.56	20.74
D	bank	13.11	16.30
E	background	17.74	14.22
F	bank	19.55	

Table 8.3: Soil moisture content as measured in the cores

For most of the samples the results appear to indicate a difference of 3% in the mean soil moisture levels between the bank and background in the first 0.1m of soil. The difference in mean percentage of water by dried weight at 0.1-0.2m was of a similar order at 4%. Figure 8.13 shows that for the background measurements, soil moisture decreased with depth whereas for the bank measurements soil moisture increased. However these results cannot be deemed significant due to the limited and random nature of the samples and the problems of extrapolating soil moisture for an area from a point data set.

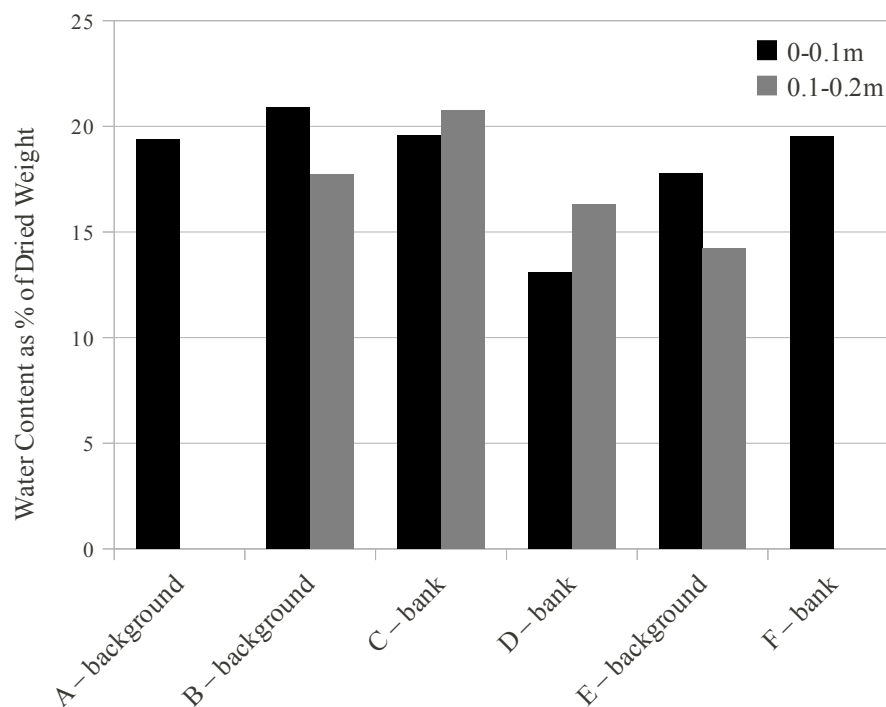


Figure 8.13: Percentage water content by dried weight for each category

8.7 Correlation of Soil Moisture and ARS data

As mentioned above, restraints on fieldwork imposed by the imperative to collect simultaneous ground based data lead to the sample size of ground based measures to be inadequate. The analysis and comparison of these samples was still conducted in order to add to the greater understanding of whether the method designed for this study could be effectively employed given more extensive data collection.

The first analysis was the spatial autocorrelation as summarised in table 8.4. As can be seen, almost all the datasets (with the exception of the ALS intensity) showed medium-high spatial autocorrelation. This means that the significance calculated for the correlation between sources will be inflated as the observations are dependant. As such the correlation results presented in

this section although still indicative, should be interpreted with caution.

	Moran's I	Geary's C
<i>If no correlation:</i>	<i>expected value = 0</i>	<i>expected value = 1</i>
Soil Moisture	0.62	0.39
Earth Resistance (0.25m)	0.99	0.008
Band 74 (1065nm)	0.92	0.04
ALS – DEM	0.97	0.2
ALS - Local Relief Model	0.78	0.4
ALS Intensity	0.2	0.79

Table 8.4: Spatial auto-correlation of the Airborne Remote Sensing data

	Earth Resistance (0.25m)	ALS – DEM	ALS - Local Relief Model	ALS Intensity	Band 74 (1065nm)
% Soil Moisture Content	-0.51	0.10	0.38	-0.56	-0.85
Significant? (p<0.01)	yes	no	yes	yes	yes

Table 8.5: Correlation of soil and Airborne Remote Sensing data

The results of the correlation of the soil moisture measurements for the top 0.1m are shown in table 8.5. Although the hypothesised negative correlation between soil moisture and earth resistance was observed in the data, the relationship was -0.51, indicating that other factors such as physical structure and salinity of the soil were likely to be contributing to the earth resistance signal. As such earth resistance measures cannot be seen as an adequate predictor of soil moisture for these data.

With regards to the topography, soil moisture was shown to have no significant relationship with the DEM. A weaker positive correlation to local changes in topography as expressed in the LRM is significant at the 0.01 level, indicating that soil moisture may be related to microtopographic change. This result highlights the importance of selecting the appropriate ALS model for comparison at the scale of topographic change associated with archaeological features.

The results of the correlation of both the ALS intensity and its corresponding wavelength in the hyperspectral data (band 74, 1064nm) also showed a significant positive correlation, although the correlation for the intensity data was not as strong as the hyperspectral data.

8.7.1 Correlation of ARS Data

In order to improve the understanding of the relative impacts of topography the correlation analysis was extended to cross-correlate all the ARS and earth resistance data (table 8.6). All figures in table 8.6 are significant to $p > 0.01$.

	ALS – DEM	ALS - Local Relief Model	ALS Intensity	Earth Resistance (0.25m)
Band 74 (1065nm)	0.24	-0.20	0.22	-0.33
ALS – DEM		-0.13	-0.07	0.21
ALS -LRM			-0.38	-0.76
ALS Intensity				0.07

Table 8.6: Cross-correlation of Airborne Remote Sensing and Earth Resistance data

It can be seen that earth resistance measures in this dataset are more closely negatively correlated with local elevation change than with soil moisture, supporting the hypothesis that for the feature surveyed, soil structure was a more important factor in determining conductivity than soil water content. No strong correlation was seen between the earth resistance survey and the DEM or the ALS intensity.

It can also be seen from table 8.6 that ALS intensity and changes in local relief are negatively correlated. Coupled with the results of the soil moisture correlation, this indicates that ALS intensity is sensitive to changes in both microtopography and moisture content but to neither exclusively. In addition it was shown that uncalibrated ALS intensity is poorly correlated to band 74 of the hyperspectral data, contrary to the hypothesis that the intensity data would be similar to data collected by a digital spectral sensor at the same wavelength. It is concluded that for this study the large number of factors that affect the quality of the ALS intensity data (2.11.4) have rendered it incomparable to hyperspectral data of the same wavelength and therefore of limited use as a substitute for data recorded by a spectral sensor.

Band 74 (1064nm) of the hyperspectral data was shown to be weakly negatively correlated to changes in local relief. Coupling these results with those in table 8.5 indicates that while both changes in microtopography and soil moisture appear to be correlated, soil moisture has a stronger correlation and therefore may be a stronger determining factor in archaeological feature visibility in spectral data.

The cross correlation analysis of ARS and ground based observations reinforced the assertion that the representation of archaeological features in any dataset is due to a combination of physical properties and allowed a broad comparison of the possible levels to which factors such as topography and soil moisture are correlated with changes in digital spectral and ALS intensity response. There remains the possibility that additional factors, particularly soil

structure which was only measured in proxy via earth resistance may not have been adequately accounted for.

8.7.2 Correlation of Soil Moisture and Hyperspectral Data

The strongest correlation observed in the soil moisture correlation analysis was with the hyperspectral band 74. Data was correlated with the 0.25m and 0.5m probe separation earth resistance data (figure 8.14) and directly with soil moisture measurements (table 8.5). As the level of significance for this correlation was 0.5, it can be seen in figure 8.14 that the 0.5m earth resistance survey is not significantly correlated to the hyperspectral data. The 0.25m is only correlated to the hyperspectral data in the visible and NIR (450nm-900nm). This result strongly indicates that earth resistance data and hyperspectral data are recording different factors (a result supported by the comparative correlations in tables 8.5 and 8.6).

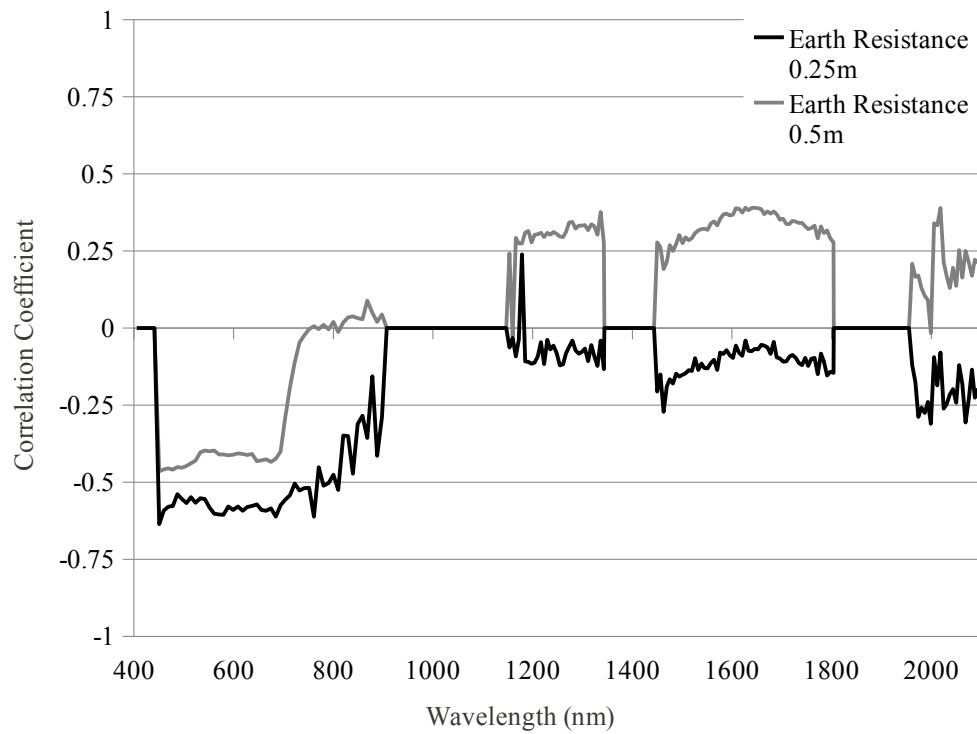


Figure 8.14: Correlation coefficient of earth resistance data across the wavelengths recorded in the hyperspectral data (Upavon)

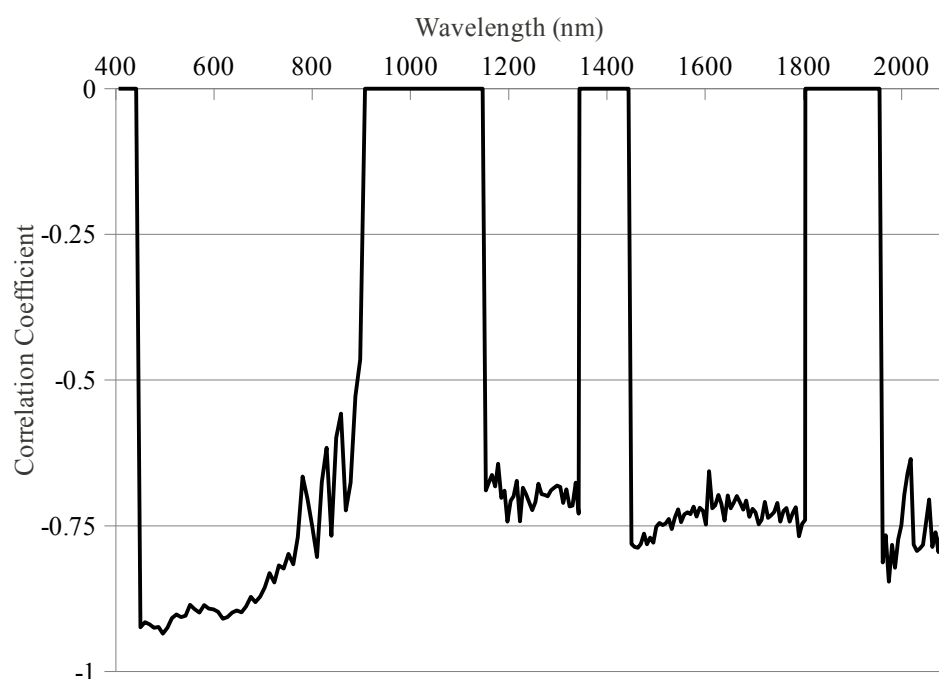


Figure 8.15: Correlation coefficient of soil moisture measurements across the wavelengths recorded in the hyperspectral data (Upavon)

As can be seen from figure 8.15, the negative correlation of hyperspectral wavelengths to soil moisture measurements for the area is greater than <-0.6 across the spectrum. The negative correlation is particularly strong in the visible and NIR portion of the spectrum (400-900nm).

It is well understood that hyperspectral data is sensitive to moisture but it was decided to test the correlation across the whole hyperspectral cube to see whether the bands that were highly correlated to soil moisture were also the most sensitive to archaeological features (as defined by the SI results section 6.5.3). As can be seen from figure 8.16, strong correlation with soil moisture measurements compares favourably with the separability of positive archaeological features in the MIR ranges (1200-1300nm) but less so in other regions. In particular, high correlation of soil moisture with hyperspectral data in the visible and NIR region (450-900nm) does not correlate with high archaeological feature separability.

Given the presence of mixed pixels in the data representing both vegetation and soil, it could be suggested that separability in the NIR is more affected by vegetation while in the MIR it may be more closely related to surface soil moisture. However it must again be stressed that the limited number of soil moisture samples gathered does not allow for solid conclusions to be drawn from these data; they are presented as indicative of the type of analysis that could be undertaken from the simultaneous collection of ground measurements.

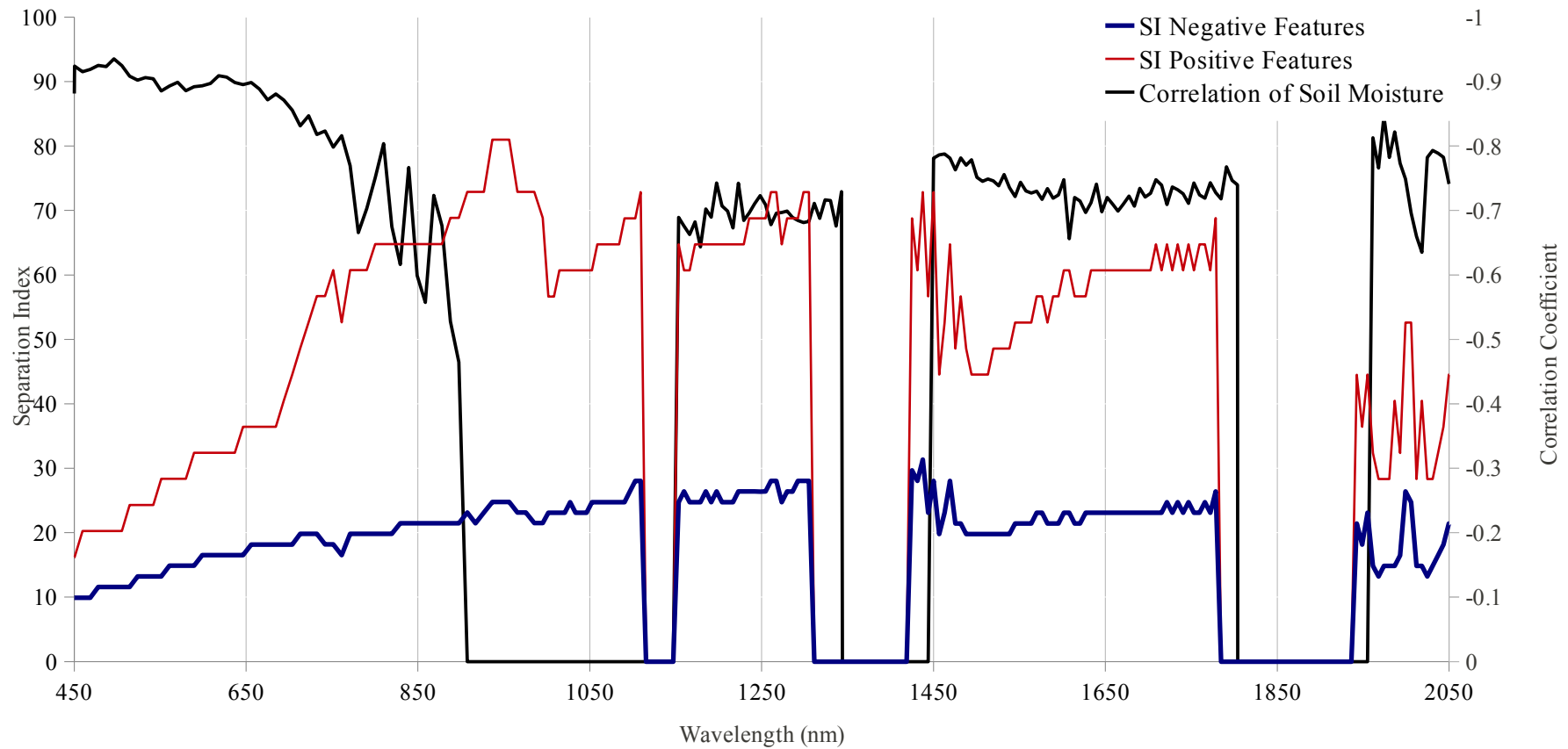


Figure 8.16: Correlation of soil moisture compared with SI the hyperspectral data (Upavon)

Comparing Feature Detection Across the Archive ARS Sources

8.8 Multi-Sensor Analysis of the Everleigh Study Area

8.8.1 Introduction

The detailed feature mapping exercise undertaken for the Everleigh Study Area, incorporating archive aerial photography, 4-band vertical photography, digital spectral and ALS data enabled the quantitative comparison of visualisation techniques necessary for Objectives 3 and 8. This was undertaken principally via the comparison of average percentage feature length. Due to the nature of the feature interpretation it was also possible to assess statistically the impact of feature type on visibility through the source data.

8.8.2 Comparison of Average Percentage Feature Length (APFL)

The APFL was compared across the sources using Friedman's ANOVA. The first twenty ranked techniques are given in table 8.7. However *post-hoc* tests showed that there is no significant difference in average percentage feature length recovery between the first eight sources in the ranking. The *post-hoc* results also indicate that there is no significant difference in ranks 1-9 when compared with the HER data, meaning that while these techniques compared favourably to the percentage recovery recorded in the HER, none of them outperformed the archive data.

Technique	Mean Rank
Brovey LRM 9 May FCC	1
Horizon View 10m	2
Overlay Jan PC1 & LRM 9m	3
Brovey LRM9 Jan FCC	4
LRM 9 m	5
HER	6
Lidar Shaded Relief PCA All	7
Aspect	8
Slope	9
Jan PCA 14 bands	10
Jan FCC PCA	11
Jan FCC (14, 7, 3)	12
May PCA 14 bands	13
Jan band 8	14
Jan band 9	15
Jan band 10	16
May FCC PCA	17
May FCC (14, 7, 3)	18
Jan MRESRI	19
Jan MRENDVI	20

Table 8.7: Results of the Friedman's ANOVA ranking the remotely sensed data sources by Average Percentage Feature Length

8.8.3 Comparing Feature Type and Visibility Across the Data Sources

The chi-squared test to identify significant differences in the recovery of feature types was applied to selected best performing visualisations for each data source. In order to do this the detailed feature types recorded were recategorised into three groups depending on their topology (table 5.8).

The results of the chi-squared analysis are given in table 8.8. It was not possible to run this analysis on the 4-band vertical aerial photography data as the expected cell counts in two out of the three types (negative and neutral features) were too low.

Four sources returned significant results indicating that there is an association between the feature type and its detectability in the technique. The first was the archive aerial photography as recorded in the HER. The chi-squared analysis indicated that feature type had a significant impact on visibility for neutral and negative features.

The analyses also showed a significant association between feature type and visibility for two of the ALS techniques. The chi-squared analyses showed a significant association for the LRM 9 model ($p < 0.05$) and a very significant association for the PCA transform ($p < 0.001$). Significant association was shown for the overlay of the January PC1 of 14 bands and the LRM 9 model, though not the Brovey transformation.

For all other techniques tested, the chi-squared analysis showed that there was no significant association between feature type and visibility, indicating that in the broadest categories the type of feature did not impact on its visibility in the airborne remotely sensed data.

Source	Technique	χ^2	$p<0.05$	$p<0.001$	Cramer's V	Significant association between feature type and visibility?
Archive Aerial Photography	SMR data	35.01	√		0.45	Yes
January Spectral Data	Band 8	0.76	√		0.07	No
	PCA all bands	1.34	√		0.89	No
	FCC	1.58	√		0.1	No
	FCC PCA	2.13	√		0.11	No
	MRESRI	2.4	√		0.3	No
May Spectral Data	Band 8	2.57	√		0.12	No
	PCA all bands	0.13	√		0.03	No
	FCC	1.14	√		0.08	No
	FCC PCA	0.27	√		0.04	No
	MRESRI	2.5	√		0.12	No
Lidar Data	Aspect	5.79	√		0.19	No
	Slope	3.55	√		0.16	No
	PCA	15.21		√	0.3	Yes
	Horizon Modelling (10m)	5.45	√		0.18	No
	LRM (9m)	10.97	√		0.25	Yes
Overlay	LRM / Jan PC1 overlay (addition)	9.93	√		0.22	Yes
	Brovey LRM / Jan FCC	1.52	√		0.10	No
	Brovey LRM / May FCC	2.39	√		0.12	No

Table 8.8: Results of the chi-squared analysis for feature type and visibility across all data

8.8.4 Cross- Data Comparisons

One of the aims of the research was to identify combinations of remotely sensed data that allow mapping of the archaeological resource to best effect (Objective 8). Table 8.9 illustrates the combined recovery rates from multiple data sources. The results presented are divided into three sets of data for comparison; manual combination of the results of all the visualisation techniques trialled; the manual combination of the best performing single visualisations; and the digital combination of data prior to feature mapping.

From the manual combination of the results of all the visualisations, it can be seen that the combination of ALS and digital spectral data is particularly useful, with a recovery rate of 83% of all previously known features and almost 92% of all features when both spectral datasets are used in conjunction with the ALS data. When the results of the spectral data analysis from either season is combined with the ALS, c.80% of previously known features were recorded. This result may indicate that the January spectral data had more commonality with the ALS data, as the margin of better detection of features in the January data over the May data is not upheld when the sources are combined with the topographic data. Of the various combinations trialled, the addition of ALS and spectral data captures a high proportion of the features that were already known in the HER (column 4, table 8.9) making it the closest parallel to the record created from archive aerial photography.

In contrast it can be seen that neither the 2006 nor 2007 4-band vertical photography significantly improved the recovery rates of features from combined ALS data alone. The usefulness of the broad 690nm-1000nm NIR band of the vertical air photography for enhanced archaeological feature mapping was also called into question by the fact that in both years the number of features mapped from the visible and NIR bands was almost equal.

High percentage archive and total recovery (columns 4 and 5, table 8.9) can also be seen in the combination of best single visualisation techniques. On average the combination of single techniques produced feature recovery rates of 8-15% fewer features than the combination of all visualisations. The best performing combination of single visualisation techniques (ALS LRM + 14 Band Jan PCA + 14 Band May PCA) recorded 9% fewer features.

	Number of features recovered	Number Previously known (in SMR)	% recovery of archive (SMR) (n=89)	% recovery of total known (n=170)
Manual combination from all visualisations				
ALS (all)	123	68	76.40	72.35
ALS (all) + Jan Spectral (All)	139	71	79.78	81.76
ALS (all) + May Spectral (All)	143	72	80.90	84.12
ALS (all) + Jan Spectral (All) + May Spectral (All)	155	74	83.15	91.18
ALS (all) + AP2007 (all)	123	68	76.40	72.35
ALS (all) + AP2006 (all)	123	68	76.40	72.35
ALS (all) + AP2006 (all) + AP 2007 (all)	123	68	76.40	72.35
ALS (all) + AP2007 (All) + Jan Spectral (All)	139	71	79.78	81.76
ALS (all) + AP2007 (All) + May Spectral (All)	143	72	80.90	84.12
ALS (all) AP2006 (All) + AP2007 (All) + Jan Spectral (All) + May Spectral (All)	155	74	83.15	91.18
Jan Spectral (All) + May Spectral (All)	110	56	62.92	64.71
AP 2006 (All) + AP 2007 (All)	85	51	57.30	50
Best performing single visualisation for each data source				
ALS LRM	92	51	57.30	54.12
ALS LRM + 14 Band Jan PCA	120	60	67.42	70.59
ALS LRM + 14 Band May PCA	118	62	69.66	69.41
ALS LRM + 14 Band Jan PCA + 14 Band May PCA	140	66	74.16	82.35
ALS LRM + Jan Band 8	115	59	66.29	67.65
ALS LRM + May Band 8	116	60	67.42	68.24
ALS LRM + Jan Band 8 + May Band 8	132	63	70.79	77.65
Digital combination				
Brovey May	100	59	66.29	58.82
Brovey Jan	94	53	59.55	55.29
Jan band 8 LRM Overlay	97	56	62.92	57.06

Table 8.9: Previously known and total features mapped by combining visualisation techniques and sources

8.8.5 Comparing Uniqueness

Table 8.9 shows that even using all visualisation methods no single source recorded more than 72% of all the features in the study area. This indicates a high level of complementarity between the data sources. To further investigate this observation, the number of features unique to each data source was compiled into a comparison table 8.10 below. These figures are also represented as percentage of the total number of features recorded during the study.

In general the numbers of features unique to each data type are relatively low with the ALS data, recording in the region of 15% of the total number of features recorded as uniquely visible, with the archive spectral data from different flights performing equally well (6-8%). A discrepancy can be seen in the January spectral data between the best performing band and the results of all the visualisations, with the combination of all techniques performing much more strongly in terms of uniqueness than the 14 band PCA in comparison with the other sources. This is an indication of the wider spread of uniqueness across the wavelengths of the data set and the relatively poor performance of the PCA analysis in comparison to uniqueness for the individual bands (section 7.4.6). Table 8.10 also shows the poor performance of the 4-band imagery in comparison with the other sensors with no unique features recorded from these data.

Comparing All data	Number of Unique Features	Percentage of Total number of features recorded (n=170)
ALS (All)	27	15.88
Jan Spectral (All)	10	5.88
May Spectral (All)	13	7.65
SMR (compared to all)	15	8.82
2006 AP (All)	0	0
2007 AP (All)	0	0
Comparing single best performing visualisations		
ALS LRM 7	28	16.47
Jan Spectral 14 Band PCA	18	10.59
May 14 Band May PCA	14	8.24
SMR (compared to single best performing visualisation)	23	13.53

Table 8.10: Number of unique features detected in each data set (4-band vertical aerial photography shortened to AP (All))

8.8.6 Feature Certainty

The nature of the archaeological resource means that the certainty with which features can be identified solely from airborne remote sensing techniques will always be limited. However the certainty of identification and interpretation is greatly enhanced when the feature can be identified in data from multiple sources. As an indication of certainty, the number of features mapped in multiple sources is presented in table 8.11. However as each sensor records different aspects of a feature (topography, proxy vegetation change) these figures can only ever provide a very general indication as to the validity of the interpretation.

Feature Certainty	Number of Features	Percentage of Total Recovered
Detected in one source	65	38%
Detected in two sources	49	29%
Detected in three sources	24	14%
Shown in all	32	19%
Total Number mapped in more than one source	105	62%

Table 8.11: Table showing the number of features mapped in multiple data sources

Unfortunately there are no contemporary ground observations for the 65 unique features identified from the ALS and spectral data and the nature of the landscape and large scale of the features means that of these, 32 unique features that are likely to have surviving topographic elements were impossible to identify in the field visits that accompanied this study. The next step in this analysis would be to take a sub-sample of the 65 unique features and apply non-airborne techniques such as geophysical survey or trial trenching to determine how many of these features can be verified by some other method.

8.9 Comparison of 'Traditional' vs 'New' visualisation techniques for ARS (Everleigh)

8.9.1 Introduction

Objective 9 of the research required a quantitative comparison of standard and advanced techniques for airborne remote sensing visualisation. As detailed in the Data chapter (Chapter 5), two stages of feature mapping were undertaken in the Everleigh study area. Initially Areas A and B were used producing a total of 290 features of archaeological origin (figure 8.17). These areas were subjected only to single band, TCC and FCC analysis for the spectral data and PCA of eight shaded relief models for the ALS data, reflecting the techniques that were identified as being most commonly applied to these data types, henceforth termed “traditional techniques”.

Area C was identified as a representative subset of Areas A and B for further interrogation. In this area a total of 170 archaeological features were mapped using a much wider variety of techniques. This allowed the comparison of 'Traditional' vs 'New' techniques as outlined in Objective 8.

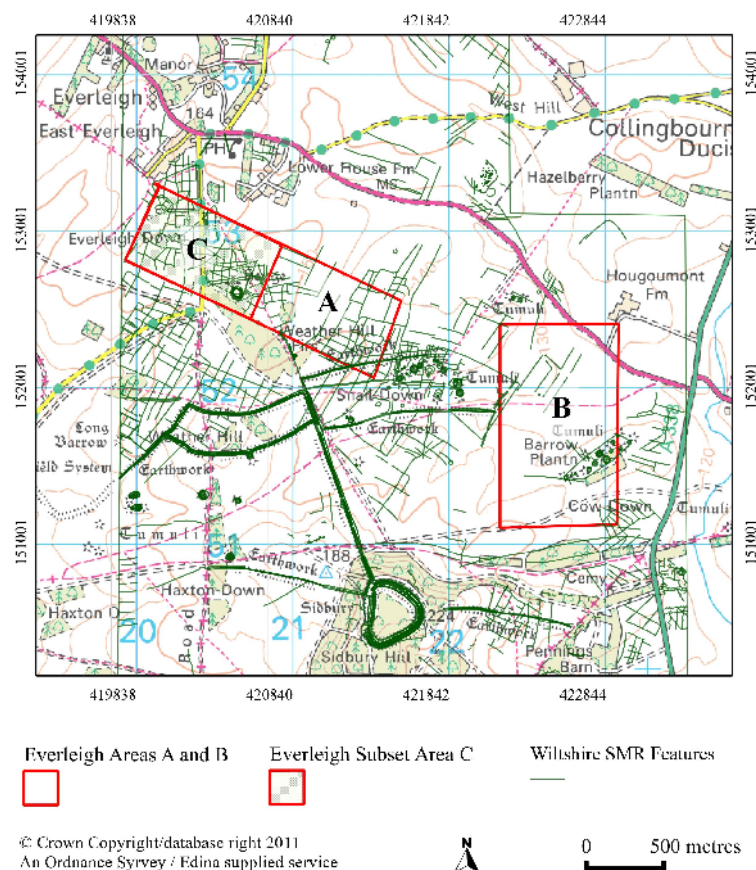


Figure 8.17: Everleigh Study Areas A, B and C location map

Throughout this section where percentage of the total number of known features is given this number represents the proportion of total number of features known from both archive archaeological records in the form of the Wiltshire HER and the results of this study. These figures cannot be seen to be the same as the total number of archaeological features present as it would be impossible to identify all archaeological features in any landscape from airborne remotely sensed data. However, representing the rate of detection of archaeological features as a proportion of the total known is extremely useful for comparing data sources, and may provide a guide for the quantity of archaeological features in an area providing this caveat is acknowledged.

8.9.2 Comparison of 'Traditional' vs 'New' techniques for Areas A/B and C

The number of features recorded for each data type for the study areas A/B and C are shown in table 8.12. These figures in the case of the spectral, ALS and 4-band aerial photography are the total number of single features mapped across all the visualisation techniques applied. The results are illustrated in terms of percentage recovery of all known features in figure 8.18.

It can also be seen from figure 8.18 that the most efficient method for identifying archaeological features, and the only survey type that outperformed the HER record was the ALS data.

	Number of features recovered from Areas A/B using standard techniques (total 290)	Number of features recovered from Area C using 'traditional' techniques (total 161)	Number of features recovered recovered from Area C using all techniques (total 170)
HER (baseline)	151	89	89
4-band AP 2006	57	37	37
4-band AP 2007	45	34	34
January Spectral	128	62	82
May Spectral	112	62	69
ALS	159	92	123

Table 8.12: Table showing the number of features recovered from each of the study areas.

In area A/B the total number of sites known after the analysis (290) was 92% higher than that identified in the existing HER record (151). In area C using traditional techniques the increase was slightly smaller from 89 to 161 features, a rise of 81%.

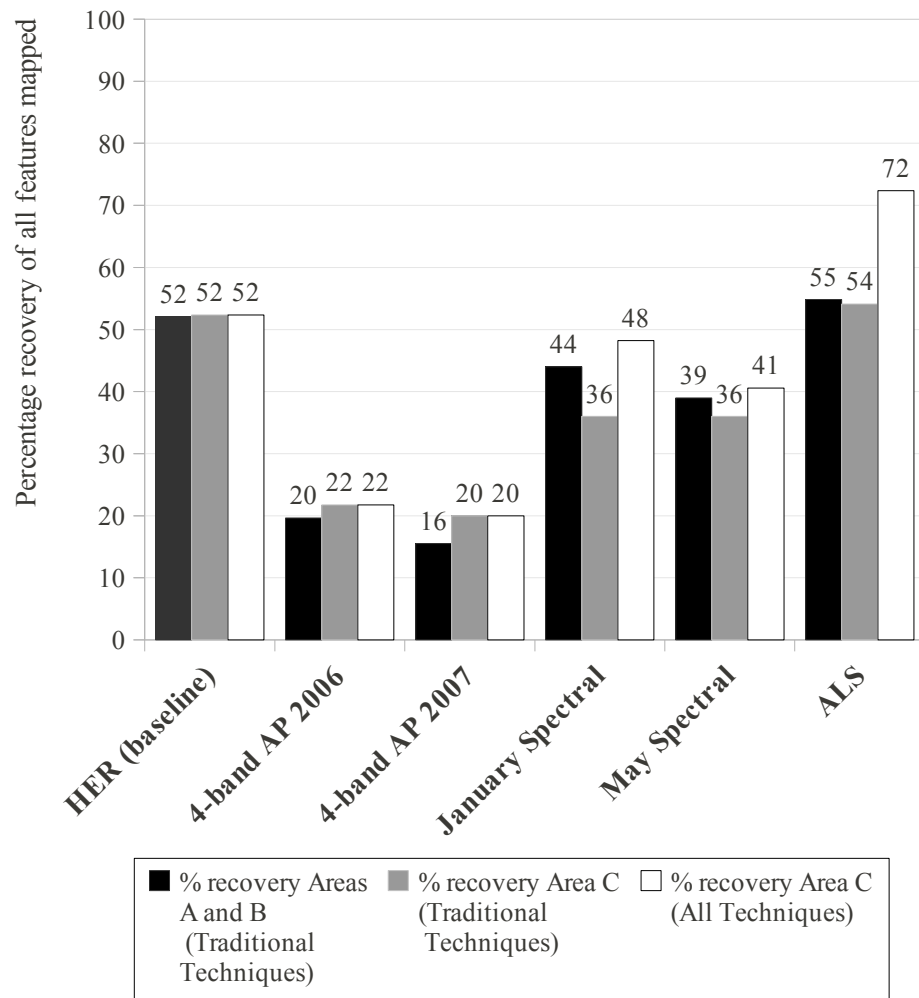


Figure 8.18: Percentage feature recovery for Areas A and B (using traditional techniques) compared with both traditional techniques and all techniques for subset Area C

Figure 8.18 shows that in area C using all the techniques applied there was an increase of 18% to the number of features seen in the the ALS data and a smaller increase of 12% for the January and 5% for the May spectral data. Overall the increase in the total number of features identified was just 6% from the traditional techniques compared with all techniques.

The increased identification of features in multiple datasets shown in cross comparison table 8.13, is extremely important for improving the accuracy of the archaeological interpretation. For example, it can be seen that using traditional ALS and spectral techniques 36 features were recorded in both the ALS and the January spectral data. The additional techniques trialled for Area C raised this number to 66.

	Wiltshire HER	ALS Traditional	ALS All Techniques	January Spectral Traditional	January Spectral All	May Spectral Traditional	May Spectral All
Wiltshire HER	89	48	68	37	48	38	41
ALS Traditional		92	92	36	48	35	37
ALS All Techniques			123	51	66	46	49
January Spectral Traditional				62	62	27	30
January Spectral All					82	38	41
May Spectral Traditional						62	62
May Spectral All							69

Table 8.13: Cross comparison table showing the number of features recovered by any two sources

Summary of Results

8.10 Meeting the Objectives

The quantity and quality of data available for this analysis meant that it was possible to achieve the technical objectives established in chapter 3, and the results for each objective are summarised below.

8.10.1 Objective 3 – Assessing the Relative Value of ARS data

- The analysis of archive ARS data for the Everleigh Study Area gave an opportunity to compare feature detectability to an existing archive in the form of the HER (archive aerial photography transcription). The combination of sensors increased the number of detected archaeological features in areas A and B by 92%.
- In this predominantly grassland environment, archaeological features were most detectable in the ALS data. The combination of all ALS visualisations for Area C recovered 75% of features known from the HER and 72% of the total number of features recorded. The ALS data were also statistically shown to be unaffected by land use.
- The digital spectral data were shown to be of value in this environment for detecting archaeological features despite their relatively low spatial resolution. In the January data, 48% of all features recorded in the analysis and 54% of the features known from the HER were detected in Area C. In the May data, 41% of all features and 43% of HER features were detected in Area C. Both spectral datasets recorded unique features, however feature detection was shown to be significantly impacted by land use variation across the study area.
- The 4-band NIR photography performed poorly in comparison to the other data, recording just 20-22% of all features in Area C and no unique features. These results indicate that despite their higher spatial resolution, these data are less well suited to archaeological feature detection in this environment than digital spectral imagery, ALS or archive aerial photography.
- The key finding of the analysis of archive ARS data was the complimentary of the different sensors. No single technique recorded more than 72% of all features and high levels of complementarity were observed between spectral and topographic data.

8.10.2 *Objective 4 – Understanding Environmental Conditions*

- Although the full understanding of environmental conditions at the time of archive data collection is not possible without contemporary, co-located observations, it was possible to collect relevant data for average rainfall from weather stations local to the study area to give an insight into ground moisture conditions.
- The analysis of soil data from the Upavon Study Area indicated that variation in soil moisture levels over archaeological features could be a significant factor in their detectability in airborne spectral data.
- Further to this assertion, it was noted that improved feature detectability in the spectral data appears to be related to a short period without rainfall immediately prior to the acquisition for both the archive and planned data. However, the sample size was too small to suggest a statistically significant correlation.

8.10.3 *Objective 5 – Deriving Quantitative Information from ARS*

- Feature degradation was documented in the Everleigh Study Area in field system elements that ran through three land use types. Features in the heavily ploughed area could still be detected in the ALS data and relative heights derived from the LRM.
- The most important results contributing to this objective relates to the analysis of accuracy in the ALS models specifically the LRM. Using contemporary GCPs it was possible to quantify the error present in ALS models, underpinning future analysis of degradation.

8.10.4 *Objective 6 – Applying 'New' Techniques*

- Quantitative assessment of a number of visualisation techniques for the ARS data showed that on the whole “new” techniques, such as LRM and Horizon View Modelling improved feature detection rates by 18%.
- “New” visualisation techniques (PCA and vegetation indices) were also shown to improve feature detection in the spectral data but by a smaller margin (5% for the January and 12% for the May spectral data).

8.10.5 Objective 7 - Spectral Sensitivity

- Visual assessment of sensitivity across the wavelengths of the archive multispectral data showed that in both January and May archaeological features were more detectable in the red-edge wavelengths (around 770nm) than in any other region represented.
- Automated assessment of the hyperspectral data using SI supported the results of the visual assessment but also showed increased sensitivity in the NIR and MIR regions . It was also illustrated that separability was not equal for all feature types.
- For the archive spectral data, archaeological feature detection was shown to be better in January than in May.
- Land use was shown to have a significant impact on the visibility of archaeological features in the archive spectral data for the Everleigh study area.
- Archaeological spectral sensitivity in the hyperspectral data for the Upavon Study Area was shown not to be solely comparable to soil moisture correlation as measured by earth resistance survey.
- The value of data recording specific wavelengths (multi or hyperspectral) compared with broad-band, averaged NIR photography was illustrated by substantially higher feature recovery rates despite lower spatial resolution.
- PCA was proved to be a useful way to summarise spectral data but was also shown to mask archaeological information in certain wavelengths.
- Vegetation indices were shown to provide little complementarity data in this environment, with most performing poorly compared with individual bands in the archive data assessment.

8.10.6 Objective 8 – ALS Visualisation Techniques

- The complementarity of ALS visualisation techniques was shown, illustrating that a single technique is not sufficient to detect all archaeological topography in this environment.
- Two new techniques, Horizon View Modelling and LRM were assessed and found to be of use for identifying microtopographic change in this environment.
- Horizon View Modelling, despite good feature visibility was shown to be susceptible to linear artefact creation.

- LRM was shown to be a useful feature detection technique and also proved to be more suitable for digital combination with other data than the DEM.
- Shaded relief modelling and PCA of shaded relief models, although aesthetically pleasing, were shown to be the least accurate techniques for locating and profiling features.
- In this environment, land use was shown to have no significant impact on feature detectability for any of the ALS visualisation techniques.

8.10.7 *Objective 9 – ALS Model Accuracy*

- Through contemporary GCPs it was possible to verify the accuracy of the DEM over archaeological features.
- A new technique based on change in slope was developed and applied to assess the accuracy of depiction of microtopography in the LRM.

8.10.8 *Objective 10 – ALS Intensity*

- ALS intensity measures for the archive EA data were shown to be unsuitable for archaeological feature detection in this study.
- Histogram matched intensity data were also shown to have a relatively poor correlation to the closest band of the hyperspectral data, indicating that more complex radiometric calibration is required for useful results.

8.10.9 *Objective 11 – Comparison of Ground Geophysical Techniques and ARS*

- Through the ancillary meteorological data it was possible to derive an hypothesis regarding the impact of soil moisture on archaeological feature detectability.
- Direct and proxy measurements of soil moisture were compared to ARS data and shown to be correlated with hyperspectral data values. Some of the spectral regions sensitive to moisture were also sensitive to archaeological features.
- Earth resistance was shown to be a poor proxy for soil moisture in this environment, being affected by feature structure, compaction and salinity of the soil.
- GPR survey was not useful in determining the subsurface structure of the feature sampled.
- Multicausality and spatial autocorrelation were shown to be affecting the usefulness of

results of the correlation analysis between ground based and airborne methods, rendering this an insufficient tool for of comparison of data.

8.10.10 Objective 12 – Digital Integration of ARS Data

- Simple raster mathematics was show to be an ineffective way to combine data, despite careful scaling of the source rasters.
- The ALS-derived DEM proved to be unsuitable for digital integration. The LRM was shown to be a more effective terrain model for both simple raster mathematics and pan (Brovey) sharpening.
- Pan (Brovey) sharpening of the spectral FCC image using the ALS LRM model gave the best results in terms of feature detectability. Even so, this was shown to reduce feature detection by 13-20% compared with the individual analysis of the source rasters.

9 Discussion

9.1.1 Introduction

This chapter draws together and examines the new information derived from the study of airborne remote sensing data for the Salisbury Plain study areas. The chapter is divided into three, with a section specific to each of the main data types used. The results of the analysis of digital spectral data are discussed first (9.2) with respect to previous understanding and future directions for this research area. A similar approach is taken for ALS data (9.3). The final section (9.4) discusses the implications of the findings of the project to the broader application of airborne remote sensing to archaeological research.

9.2 Digital Spectral Data for Archaeological Prospection

9.2.1 Introduction

The systematic approach employed in this study was inspired by the work of Traviglia (2006) , Hampton (1974) and Shennan and Donoghue (1992), but is atypical when compared with recently published archaeological studies of spectral data (e.g. Challis et al. 2009) (see section 3.6). Analysing many visualisations for the same area is time consuming, and may be problematic as there is a tendency once a feature is mapped, for an operator to continue to “see” a feature in subsequent visualisations. However so little was known about the impact of visualisation techniques on archaeological feature detection prior to this research, that any strategy without thorough assessment of a range of techniques would have failed to improve current understanding.

As the review of current research has demonstrated, the use of digital spectral data for the identification of archaeological features in a non-arable environment was also a novel application (section 3.6 b). As such, in the grassland environment that typifies the Salisbury Plain study areas it was difficult to predict the potential of these data at the start of the study, particularly given the lower spatial resolution of airborne spectral data compared with standard aerial prospection techniques. The results of the analysis of both archive data and digital spectral data from planned acquisition have been promising in terms of feature identification when compared with other sensors, paving the way for future applications of digital spectral data in non-alluvial environments.

9.2.2 Comparison to Other Sensors

A key objective of the research was to assess the relative value of digital spectral data when

compared with both the existing archaeological record (HER) and other ARS data, specifically NIR photography and ALS data (objective 2). Incorporating the assessment of many visualisation techniques (Objective 5) and building from visual detection of features to automated assessment of separability, has enabled quantitative assessment of the value of digital spectral data when compared with other ARS data.

The archive multispectral data performed well in comparison with the baseline data from the Wiltshire HER, with around 42% of features that were recorded in the HER also being detected in the individual January and May datasets. When the data from both seasons were combined this number rose to 63% (section 6.4, table 6.2), indicating the complementarity of seasonal data and the value of repeat acquisitions capturing different soil and vegetation conditions.

The feature detection rate is particularly surprising given that the HER comprises the transcription of an archive of more than 50 years of oblique and vertical, colour and panchromatic aerial photography, illustrating the capacity of spectral data to capture information on almost half of the previously known features in a single survey. Combining the results of all the sensors for the Everleigh area, 48% of all features recorded in the current study were detectable in the January data and 41% in May data which compares favourably with the 52% recorded by the HER.

Often lower spatial resolution is cited as an inhibiting factor for using spectral data, however the results of the feature mapping exercise indicate that in this environment the lower spatial resolution did not prevent the detection of features already mapped from aerial photography. This assertion is supported by comparison to the broad spectral coverage of the 4-band NIR photography (section 6.3). Although there have been recent advances in the use of NIR photography for detection of archaeological features (Verhoeven 2008; Verhoeven and Schmitt 2010; Verhoeven 2011), prior to the Salisbury Plain study presented here, no research had compared vertical NIR photography to multi-band digital spectral data. In comparison with the NIR photography, which had six times the spatial resolution but poorer spectral resolution, over twice as many features were detected in the digital spectral data of either date. While the broad comparison of these two datasets is hindered the lack of contemporaneity, the fact that the NIR photography performed poorly when compared with the baseline HER data (recording less than a third of previously known features) and detected no unique features, strongly suggests that for the features in this study, spectral resolution and / or seasonality were more important factors in feature detectability than spatial resolution.

As noted in the literature review (Chapter 2), only one previous study (Rowlands and Sarris 2007) had directly compared the results of feature detection from digital spectral and ALS data

and no work of this kind had been undertaken in the UK (section 2.4.2). By incorporating ALS data, the current research has demonstrated the benefit of multi-sensor survey, particularly for improving feature interpretation, which in the past has proved problematic from digital spectral data alone (Winterbottom and Dawson 2005). Consequently, it is suggested that the quantitative comparison of the feature type from aerial data was only really possible via the incorporation of ALS data. For January a total of 74% of the number of features detected were also detected in the ALS, while in May the number was slightly lower at 71%. This is comparable with the percentage of HER features that had topographic representation (76%). The statistical analysis shows that there was no significant association between feature type and visibility in the digital spectral data, but that there was a significant association between land use and feature visibility. The fact that only a quarter of the features seen in each spectral dataset can be classified as “neutral” (i.e. soil or vegetation marks with no detectable topographic change in ALS or walkover survey) is attributed to the spread of feature types in the study area where only 13% of the total number of features detected fell in this category. In this respect the spectral data appears to be slightly more sensitive to this feature type than the HER record, where 17% of features recorded were without currently detectable topography.

The results of the data comparison have highlighted the contribution of archive digital spectral data can make to the assessment of archaeological features in a predominantly grassland environment, detecting features that were previously unknown and have no detectable topographic representation. Perhaps the most significant result is the difference in feature recovery between the January and May acquisitions (section 9.2.3). This illustrates that digital spectral data are not only complementary to other ARS data but that multiple spectral surveys with the same instrument over the same landscape can improve the feature detection rate and provide complementary data. Our understanding of the exact mechanisms behind feature detectability in archive spectral data is severely limited by a lack of contemporary ground observations, but some ways forward using archive weather observations are discussed in section 9.2.4 below.

9.2.3 *Spectral Sensitivity*

Particular priority was given to assessing sensitivity across the visible – NIR spectrum in the this research (Objective 6). Given the lack of previous study of spectral sensitivity (section 3.2), this was deemed fundamental to improving understanding of how to apply and interpret airborne spectral data for archaeological prospection.

The initial approach of single band mapping for the archive multispectral (CASI) data worked well for the Everleigh area showing that not all regions of the NIR spectrum were equally

sensitive to archaeological features. This work broke new ground in the analysis of NIR spectral sensitivity for archaeological data, using established methods of archaeological aerial prospection to record features across the spectral bands. Even the detailed comparisons of visualisation techniques undertaken by Traviglia (2006; 2008) did not include single band analysis only band ratios, PCA and vegetation indices. From the results of the Salisbury Plain study, it is argued that without some *a priori* understanding of sensitivity across the spectral bands it is not possible to select appropriate indices and ratios for band combinations or to quantify data loss from such data combinations compared with single band analysis.

In both the January and May datasets the red-edge wavelengths (680-730nm) allowed the best detection of features in visual assessment (section 6.2.4). The May data also showed a small peak in detectability in the visible region (470-550nm) when compared with the January data, it is suggested that this relates to the senescence of vegetation in the latter data. Generally both January and May spectral acquisitions for the archive digital spectral data show sensitivity to archaeological features that matched what would be expected of a spectral vegetation response with significantly higher response in the red-edge NIR than the visible. In the January and May data, features recorded in the best performing band (706-717nm) represented 67-8% of all features detected in each spectral acquisition. This indicates that the localised changes in matrix detected that are recognised as archaeological features in the spectral data are principally related to changes in vegetation. Therefore in the wavelengths where the vegetation response is strongest, the contrast between archaeological features and their surroundings is also most detectable. This has significant implications for the application of NIR wavelengths for prospection, not only in identifying the key spectral region for feature detection but also in highlighting the importance of the vegetation component of the spectrum in this environment. This improved understanding shows how the method of this research can contribute to a better understanding of the science underpinning feature detection (section 3.6 a).

In terms of spectral sensitivity, the value of higher spectral resolution to archaeological prospection was indicated by comparison with the archive NIR photography (section 6.3). The NIR photography had a very broad NIR range from 690-1000nm, the averaging of which appeared to impede feature detection. The comparison of NIR photography with digital spectral data is most fairly done through the false colour composites (as the NIR photography could not be viewed as single bands) and in all cases the FCC of the NIR photography recorded less than half the number of features of the FCC of the spectral data. Having recorded high spectral sensitivity in the red-edge, this indicates that broad NIR measurements are insufficient to detect the changes that are noticeable in narrower spectral bands in this environment.

The hyperspectral data for the Upavon study area required a different approach to assessing

sensitivity due to the high number of bands recorded and so an automated approach in the form of the Separation Index (Cavalli et al. 2009) was trialled. In principal this index appeared to be a rigorous method of assessing separability but on application it was found to be heavily dependent on a number of factors including the range of spectral values and the ratio of background to archaeological pixels (section 6.5.2). This meant that the published version of the index was unsuitable for landscape-scale assessment and led to the modifications detailed in section 5.7.1. The issue of value range also rendered the SI an unsuitable tool for comparison of vegetation indices (section 6.5.3) casting doubt on the claims of the authors that the SI “can be applied to R.S. (ARS) data regardless of the land cover scenario, the sensor data characteristics and the applied image processing techniques” (Cavalli et al. 2009:274).

Despite this, the modified SI proved to be a useful tool for inter-band comparison across the spectral cube. Although, unlike the visual assessment undertaken for the archive data, this technique could not take into account features newly detected in the spectral data, it provided a way to compare separability of known features from the background spectral values in an area of homogeneous land cover and also to assess the impact of feature type on detection rate (section 6.5.2). In comparison with the archive spectral data, it was shown that the red-edge region still showed high separability, but that there were also peaks of separability in the 1100-1150nm and 1300-1340nm regions illustrating the value of wavelengths longer than those recorded by the CASI sensor. Feature type was seen to have a significant impact on separability in this data with SI values for negative features much lower for those with positive topographic expression. Features with no topography were the most difficult to separate from the background though this could in part be due to inaccuracies in the HER record locations which could not be corrected using contemporary ALS survey and aerial photography.

While the results point to microtopography as being a significant factor determining feature detectability in this environment, investigation of non-topographic features should be prioritised for future work with hyperspectral data. These features are the most difficult to detect using other sensors and thus are the examples where the application of digital spectral imagery could be of most benefit. The correlation observed between NIR regions of increased archaeological separability and sensitivity to soil moisture also indicates that this could also be a key factor underlying detectability. However, from statistical analysis of the soil moisture samples and microtopography for Upavon Field Site 1, it is clear that these factors are not independent, and therefore determining their relative impact on visibility may be impossible for features with even slight local relief.

The modified SI was shown to be a useful tool for assessing the detectability of known features in large hyperspectral datasets, providing the accuracy of the existing archaeological spatial

record could be verified and corrected if necessary (section 4.5.2). It was not possible to assess the detectability of previously unknown features that had no topography during the time frame of this study. Defining target features for this type of analysis would be very challenging, in part because in this environment, features with no upstanding topography are rarely detectable by any form of aerial survey and as ground survey is challenging and offers limited spatial coverage, sites of this type are difficult to locate. Further detailed transcription of the hyperspectral data may provide potential features, however it is considered that greater priority should be given to defining the physical and biological properties that enable the detection of known sites, so as to aid the theoretical identification of target features that do not have these parameters. As such the SI provides a method of data reduction and definition of wavelengths most sensitive to archaeological prospection.

9.2.4 Seasonality

Objective 4 outlined the need to assess the impact of seasonality on archaeological feature detection in spectral data. Seasonality is a factor that is widely acknowledged to have an impact on feature detectability (Shennan and Donoghue 1992; Wilson 2000; Brophy and Cowley 2005; Traviglia 2006; Challis et al. 2009; Beck 2011) but has proved difficult to research due to the lack of repeat acquisitions over the same area at different times of the year; a factor that links back to the dependence for the most part on archive ARS data for archaeological prospection (section 2.3.2). Ultimately, only a continuous measurement approach that involves daily monitoring of soil conditions combined with airborne spectral measurements (such as that currently being trialled by the DART Project (Beck 2010)) will collect the scientific data required to determine seasonality in a given environment. Even given this detailed dataset, the potential for modelling detectability across entire archaeological landscapes encompassing varying geological, environmental and vegetation conditions may prove impossible given the number of factors affecting detectability.

This research has shown that assessing the impact of seasonality can be undertaken using archive data, with the CASI data collected in January and May 2001 providing a unique opportunity to do this (section 6.4). While it is acknowledged that this repetition of survey may be uncommon and the lack of contemporary ground observations is a limiting factor, the possibility for using archive airborne data to assess seasonality is one that has been ignored to date.

Contrary to what might have been hypothesised based on peak vegetation growth (Suttie et al. 2005), the January spectral data performed significantly better than the May data both in terms of binary visibility and APFL. This correlates to an extent with the results of Hampton's survey

over grassland (1974), where non-visible wavelengths were shown to be of less use in June and July than in August, although in the Salisbury Plain study NIR photography (of a similar type to Hampton's) taken in August and September performed very poorly in comparison to all other sensors (section 6.3).

Assessing the causes of this observed difference are complex due to the lack of contemporary ground observations. Hypothetically, there are several factors to consider:

- The shallow root system of hardy vegetation such as grass that is typical of liminal areas is unlikely to exhibit stress in its peak growing season (May) under non-drought conditions (such as were captured in the data used for this study.)
- The impact on vegetation is also likely to be heavily affected by the type of archaeological features in the study area. As earthen structures dominate the record it is suggested that these neither inhibit nor promote hardy vegetation growth sufficiently to be the primary cause of detectability.
- During senescence the low levels of hardy vegetation enable greater soil fraction to be detected in each pixel thus the detection of features in the January data is not a consequence of vegetation change alone but of a mixture of soil and vegetation contrast.
- If soil contrast is significantly contributing to feature detectability, over free-draining soils, the weather conditions in the days immediately preceding survey may have a significant impact on the ability to detect features in this environment.

For the archive spectral data the only ancillary data available to the study were the rainfall records collected from the Met Office. These show that for the January data and the March data collected for Upavon (which were both seen to have good detectability of archaeological features) acquisition was preceded by several days without rain. For the May data there was a peak in rainfall over the four days prior to acquisition. While with a sample size of just three surveys this can be nothing more than an observation, there is an indication that soil moisture difference is playing a role in the separability of archaeological features from their surroundings. Evans and Jones (1977) showed that the most important factor in crop mark formation was the differential availability of soil moisture, directly linked to precipitation levels. Current work by the DART group (section 3.4.3) aims to assess the impact of soil moisture variation among other factors for known crop mark sites in agricultural areas. Using the SI as a standard measure of feature detection rates in spectral data and combining this with archive rainfall data it could also be possible to explore this hypothesis with relation to visibility of known archaeological features in archive digital spectral data.

9.2.5 Visualisation Techniques

One of the challenges for this project was to research, apply and evaluate a wide range of visualisation techniques that had not been applied previously to archaeological ARS in the UK (Objective 6). For the archive digital spectral data three standard techniques were implemented, single band analysis, FCC and TCC (after Challis et al. (2009)), alongside a number techniques that have not been widely used in archaeological prospection, including PCA, sPCA and a range of vegetation indices (after Traviglia (2008)).

Applying a range of visualisation techniques was shown to increase feature detection by 12% in January and 5% in May. The improvement seen by selecting FCC bands based on the spectral sensitivity and uniqueness shown by the single band mapping showed that this visualisation technique is much more effective when based on empirical data. This is of course only possible if assessment of separability for each of the bands is undertaken prior to the creation of composites (section 8.2.4).

Comparison of the techniques showed that all-band PCA was the best single technique for visualising features from the archive data although detailed analysis showed that the technique masked information from key bands, especially in the May data where sensitivity was more evenly spread across the spectrum. Selective PCA using the three bands with the most unique features did not perform as well as the all-band PCA for this data. However as the principal components were easier to map from when shown in greyscale rather than a colour composite, all-band PCA still required the assessment of three images to capture the majority of variance. It is also likely that this technique would be much less successful for hyperspectral data due to the increased number of bands as data loss was noted in the Salisbury Plain study when compared with the single band analysis of the most sensitive wavelengths (6.4.6). Therefore selective PCA for ranges of wavelengths based on the results of the SI is proposed as the best method for data reduction and visualisation for hyperspectral data.

The application of a range of vegetation indices was a novel area of research for archaeological prospection in the UK environment, where the two previous studies to use vegetation indices had used only the NDVI (Winterbottom and Dawson 2005; Challis et al. 2009) without further justification as to how appropriate this index is for archaeological prospection using airborne digital spectral data. The results of a quantitative comparison of 12 indices selected for their empirical basis and applied to the archive spectral data, showed that the most commonly used index, the NDVI, was in fact one of the worst performing indices for archaeological feature detection. This is due to its use of a broad band red-edge designed for satellite data when the spectral resolution of the airborne data lends itself to more refined measures such as MRESRI and RENDVI. It was shown that the best performing indices varied across the spectral datasets

of different dates with only the MRESRI consistently performing well. In summary, the best performing indices allowed the detection of a number of features that were not detectable in the best single band but offered no significant improvement on the all-band PCA. While it is clear that some indices can be used to detect archaeological features successfully, a lack of understanding of both spectral sensitivity and resolution often prevents the most appropriate indices from being applied. The scoring of indices proved to be a useful way to assess their application for archaeological research. However due to dependence of the SI on the range of values in the image, it was not possible to use this technique to compare directly the efficiency of the vegetation indices of different scales. Future work should attempt to normalise the data prior to the application of the SI to enable automated comparison of vegetation indices.

Given these results and the difficulty of interpreting the results of most vegetation indices in terms of biological parameters and relating these proxy properties to the archaeological features causing them, it is considered that the focus of archaeological digital spectral research would be more profitably directed towards developing visualisation techniques based on the spectral sensitivity identified through other means.

9.2.6 *Integration with Ground Survey Techniques*

The planned and specified data collection for Upavon allowed a unique opportunity for the collection of contemporary geophysical measurements. Despite previous interest in the links between ARS data and geophysical survey (Challis et al. 2011a; Challis et al. 2011b) no previous study has been able to compare contemporary ground-based and airborne data. Consequently the experimental design of the fieldwork focused on the acquisition of simultaneous measurements for a necessarily small area.

On analysis of the literature it became clear that the representation of archaeological features in airborne spectral data would most likely be related to two factors; the form of the feature (topography) and its physical make up, in particular its soil moisture content in relation to its surroundings (Evans and Jones 1977; Ben-Dor et al. 2002; Traviglia 2005). As soil moisture content changes almost constantly (except when at the extremes of saturation or desiccation) to assess the surface components of a representative archaeological feature most affectively, auger survey, GPR and earth resistance had to be conducted on the day of the hyperspectral data acquisition.

As anticipated, the auger survey showed that there appeared to be a difference in soil moisture between the archaeological feature and its surroundings and that there was a strong negative correlation of soil moisture changes to reflectance in the hyperspectral data (section 7.7). However the results for the geophysical survey did not present the best baseline for comparison

with the spectral data, in large part due to the chalk soils and nature of the archaeological feature selected. GPR survey failed to detect any structural change across the feature, presumably because the earthen feature that was the target of the survey was homogeneous with the topsoil (Appendix 2). The feature was detectable from change in the earth resistance survey, though it was found that these changes in resistance did not correlate well to measured differences in soil moisture. Although often cited as a direct proxy for soil moisture content (Section 3.12.1), in fact earth resistance data are affected by a number of other factors such as the physical and chemical properties of the soil (English Heritage 2008). In free-draining soils such as in the study area it is likely that the earth resistance is more affected by these factors than by moisture levels, as evidenced by the poor correlation to the soil samples (section 7.7).

Although statistical analysis indicated that topography and soil moisture were factors influencing feature detectability in the spectral data, it was not possible to draw any significant correlation between spectral data and the geophysical survey in the Upavon case study (7.7). As the sample area of geophysical survey was small, both in terms of spatial coverage and number/type of archaeological features included, it is considered that this result is inconclusive as to the nature of the relationship between earth resistance survey and hyperspectral data.

The methods used here differed from previous studies in that the focus of the experimental design was on reducing temporal variation between the data collection and therefore minimising the effect of this factor on the results. In practice it was shown that the logistical difficulties of conducting simultaneous ground survey were in themselves too great a limiting factor as they reduced the amount of data that could be gathered and therefore the quality of the comparisons to airborne data. While the analysis techniques used for these data indicate that they are worthy of further investigation, the method of ground-based data collection should be revised. It would be advisable for long-term (12 month or more) monitoring of the study sites to be in place incorporating repeated geophysical and soil measurements with a number of airborne data acquisitions during the course of the study and across a range of archaeological feature types. Unfortunately such long term monitor was beyond the remit of this study.

9.2.7 *The Contribution of the Salisbury Plain Study*

The contributions of the Salisbury Plain study to advancing the use of digital spectral data for archaeological prospection can be summarised as follows:

- Demonstrated a proof of concept of the use of digital spectral data for archaeological prospection in grass-dominated environments
- The only project to assess the comparative value of multispectral vs. hyperspectral data

in terms of spectral sensitivity for archaeological feature detection

- Provided the first example of simultaneous ground and airborne data collection for spectral data in the UK
- The only quantitative comparison of visualisation techniques to include single band analysis, true and false colour composites, PCA, sPCA and vegetation indices for the same geographical area
- Significant contribution to the understanding of the impact of environmental conditions on spectral data acquisition via comparison of repeat airborne surveys and addition of meteorological data
- The study contributes to current understanding of archaeological feature properties impacting detectability in spectral data via contemporary soil moisture measurements and geophysical techniques,
- Contribution to current understanding of the impact of land use and feature type on detectability via quantitative analysis and comparison with other ARS data
- Improved understanding of the relative value of digital spectral data when compared with other ARS data, specifically archive oblique aerial photography, ALS data and vertical 4-band NIR photography.

9.2.8 *Future Directions*

The detailed analysis of airborne spectral data as part of the Salisbury Plain research has highlighted a number of themes for future research in this field.

Although the analysis of contemporary ground measurements and ALS added to current understanding of how soil moisture content and topography contributes to archaeological feature detectability there is a pressing need for more detailed study examining other physical and biological factors. In the first instance it would be useful for such research to be conducted into both direct (bare earth) features and proxy (covered by vegetation) features separately as the definition of spectral response is likely to be different for these two categories. It is suggested that research should also incorporate features where the spectral response is a mix of soil and vegetation (as seen in the Salisbury Plain spring data), however it is anticipated that greater understanding of these “mixed” features will be underpinned by the former analysis of soil and vegetation as distinct properties.

Given the important part that established geophysical techniques could play in understanding the near-surface factors determining visibility in digital spectral data, it is anticipated that there

will be continuing developments in this area of research. Key to this will be overcoming the logistical challenges posed by the need to collect ground data contemporary with the acquisition of airborne data. The multi-factoral complexity of this analysis means that removing uncertainty relating to temporal change in conditions should be a prerequisite of future work in the field. Developments in landscape scale geophysical techniques such as those demonstrated at Stonehenge by the Ludwig Boltzman Institute (LBI 2011) will enable larger area coverage than the techniques available to this project which will give more representative ground data sample for comparison with ARS coverage.

Development of processing techniques such as the modified SI that analyse spectral sensitivity in a quantifiable way should also be considered a priority. Ideally these techniques should be supported through the detailed examination of physical and biological properties noted above but the Salisbury Plain research has also shown the potential for undertaking this type of research using archive data. By selecting case studies with high quality existing aerial transcription it is possible to evaluate the potential of archive airborne spectral survey gathered for different purposes. Combining analysis of sensitivity in archive spectral data for an existing archaeological record, with meteorological data for many different land use areas could significantly expand current knowledge with relatively little expenditure. With the ARSF archive alone containing over 7000 flightlines of ATM and CASI data collected since 1995, and 2500 flightlines of Eagle/Hawk data since 2004 (Donegan pers comm 2011), it would seem that the potential for this meta-analysis exists. It is suggested, based on the Salisbury Plain study, that at very least this analysis should be carried out for existing spectral data in advance of new acquisition in the same area.

Critically, it is observed that advances in the field of airborne digital spectral data for archaeological prospection also depend on the development of improved sensor technologies and survey platforms. Although in the Salisbury Plain study, the spatial resolution was shown to be appropriate to the detection of the archaeological features that typify this environment, there is a wider disciplinary requirement for sensors with higher spatial resolution to match that of modern aerial photography.

In order to enable the repeat collections of data required to improve current understanding of the impact of environmental conditions there is also a need to implement low-cost airborne spectral survey solutions along the lines of kite and UAV photography that have been shown to be valuable for acquisition of repeat aerial surveys. If a similar system could be implemented with spectral sensors then the expansion of spectral imaging into many environments and field programmes could be envisaged, particularly where previous modes of airborne acquisition had been too costly or impractical in terms of timing to implement. As identified in the literature

review, one of the main factors that inhibits the archaeological uptake of spectral survey is the lack of understanding of its implementation over different types of environment as well as different archaeological conditions. The field of spectral detection requires an approach that can allow multiple surveys in different environments and at different times of year, to foster better links with current field programmes (and therefore ancillary geophysical and excavation data) than can be achieved currently through Research Council or commercial survey. In much the same vein as the development of aerial photography or geophysical prospection techniques, only by building the database of archaeological spectral surveys can the implications of the technique be better understood for a variety of conditions.

In summary, research to date has scratched the surface of the potential for spectral data to be used to detect archaeological features and has shown that that non-visible wavelengths have real promise for prospection of features. The need for more specific data regarding feature properties has been highlighted by the Salisbury Plain study. That this is clearly a relevant area for research is emphasised by the current £815,000 EPSRC DART project which will address some of the knowledge gaps. For airborne spectral survey to become a recognised and widespread tool for archaeological prospection there needs to be an improvement in accessibility of spectral survey for archaeological research, as without this it will not be possible to evaluate fully its potential as a technique in a range of environments. It is also noted that the archaeological interpretation of digital spectral data is greatly enhanced by combination with other ARS data, specifically ALS. Section 9.4 discusses the implementation of multi-sensor techniques incorporating both ALS and digital spectral data for future research.

9.3 ALS data for Archaeological Prospection

9.3.1 Introduction

The value of ALS for archaeological feature detection is supported by a increasing number of studies incorporating the technique. Since the publication of a special edition of *Antiquity* where lidar was introduced as a technique for landscape prospection (Bewley et al. 2005; Devereux et al. 2005) there have been more than 35 publications relating to archaeological projects that have included ALS data in some way. However only a handful of these publications have dealt with the technical aspects of using ALS data (Challis 2006; Doneus et al. 2008; Doneus and Briese 2010; Hesse 2010; Kokalj et al. 2011) and the largest body of research in the UK has been conducted on just one landscape type; alluvial valleys (Challis and Howard 2006). To add to this, despite the recognition that ALS is best applied when analysed alongside other techniques (Crutchley 2006), few published examples provided any quantitative comparison with other

data (Bewley et al. 2005; Crutchley 2009), and only one survey has explored the complementarity of ALS and digital spectral data (Rowlands and Sarris 2007). This left a significant gap in current understanding of how to apply ALS data to archaeological research.

Due to the generally good preservation of upstanding archaeological features in the Salisbury Plain study areas, it was anticipated that ALS data analysis would compare favourably to the baseline record derived from the Wiltshire HER. As such, unlike the digital spectral data, prospection for features was not the main aim of this aspect of the study. Work focussed instead on the technical assessment of visualisation techniques, providing methods for assessing the impact of visualisation on feature detection and the accuracy with which archaeological features are represented in new modelling techniques (Objectives 8 and 9). An attempt was also made to quantify the value of ALS intensity data for archaeological prospection via contemporary spectral and geophysical survey (Objective 11).

Through this research it was shown that the ALS data has tangible value for the survey of liminal areas and ephemeral features within them. In addition ALS data proved to be of vital importance as a geometric baseline for other aerial survey, allowing improved geocorrection of new and archive data. The methods developed for rigorous assessment of the ALS derived models facilitate a more informed use of the data and are the first real step in moving from the *status quo* of ALS models as aesthetically pleasing imagery to a position where full use of the 3D data content can be made for archaeological research objectives.

9.3.2 Visualisation Techniques

Perhaps the most significant result of the analysis of visualisation techniques on the detection of archaeological features was the discrepancy in visibility of features and the complementarity of techniques. Until Challis et al. (2011c) no attempt had been made to assess the range of techniques that were available for processing ALS data. The Salisbury Plain study complements the generic and observational approach of Challis et al. (2011c) by providing quantitative data for a selected environment and comparing this with the existing aerial photography transcription.

The assessment undertaken for the Salisbury Plain study showed that the visualisation techniques used have a significant impact on the detection of features and a careful strategy for their application needs to be developed for any project using ALS data (Objective 8). In particular, users should be made aware of the derivation of the visualisation techniques applied as most often these represent the effects of topographic variation (such as changes in illumination levels in the case of the shaded relief models) or other measures (e.g. slope and aspect) associated with it rather than the change in elevation directly. While these effects are

useful for highlighting microtopography, they can also misrepresent the elevation data altering the apparent horizontal location of features (figure 6.19) or exaggerating artefacts (figure 6.23). This has a detrimental impact on the ability to extract metric data for the archaeological features detected.

The PCA of shaded relief images gave an aesthetically pleasing image and successful reduction in dimensionality compared with individual shaded relief images, however the technique still resulted in several individual PC images that were time consuming to map from, with diminishing return as the PC number increased. In addition it was found that use of the Principle Component transformation removed the possibility to assess the properties of archaeological features accurately, with features showing significant distortion of location and profile due to the variation in illumination direction. For this reason, and despite the fact that shaded relief images and PCA remain the most commonly applied techniques for archaeological prospection (Challis et al. 2011c), the results of the Salisbury Plain study show that they cannot be recommended for technical assessment of microtopography.

The two 'new' visualisation techniques trialled gave comparable results in terms of feature numbers to the PCA of shaded relief images. The LRM gave the best results in terms of number of features mapped, retaining locational and topographic integrity. It was the only visualisation technique that preserved the elevation data in the original units of measure. Consequently the LRM proved a powerful basis for digital combination of the topographic and spectral data (section 9.4). However the technique is complicated to apply with many processing steps and needs to be tested and refined to anticipated feature size for each location.

The Horizon View technique performed well in terms of number of features detected and APFL, however the derived images were also found to have location and profile distortions that were detrimental to feature characterisation. The processing also incurred many artefacts leading to false identifications, particularly so for linear features. This assertion is supported by the fact that the horizon view model showed no statistical bias for feature type (unlike the other topographic models). While ancillary data in the form of field survey or other aerial imagery is helpful when separating artefacts from genuine features, comparisons can be inconclusive due to a variety of factors including different spatial resolutions, temporal sensitivity and the fact that other sensors record different feature parameters. This research has shown that these artefacts can often be better identified by comparing different ALS visualisations, providing justification for the application of more than one visualisation technique.

Uniquely the Salisbury Plain study was able to quantify the impact of applying multiple visualisation techniques. The application of several visualisation techniques was shown to

improve the number of features detected from the ALS data by 18% from the PCA of shaded relief images alone. The fact that each technique trialled recorded 75% or less of all the features detected in the ALS data also illustrated the complementarity of different visualisations, with the strongest combination of techniques coming from the LRM and Horizon View models which together accounted for 94% of ALS features. The research showed that the application of two or three carefully selected techniques is preferable to using a single technique.

The Everleigh study relied on archive ALS data and it could be argued that certain models may produce better results given higher spatial resolution data that were subjected to improved filtering techniques to reduce artefacts. However the ALS data used are representative of the type of data most frequently available to heritage professionals and as all models were created from the same DEM the comparison between them is fair.

9.3.3 Accuracy Assessment

The data gathered for the Upavon study area allowed the first quantitative assessment of the LRM against profiles of archaeological features that were measured with kGPS (Objective 9). In order to do this it was important to develop a method of comparison of features that was independent of the scale of the original raster values. Using simple trigonometry to analyse change in slope between points along a profile was a useful technique that enabled assessment of the accuracy with which the LRM portrays the scale of microtopographic change.

Despite the increasing number of visualisation techniques, such direct tests of model accuracy are rare principally due to the lack of contemporary ground observations. No published examples of accuracy assessment of archaeological microtopography using kGPS were found during the literature review, highlighting the fact that quantitative assessment of the accuracy of feature representation in ALS data is rarely considered when the data are used for visualisation and mapping. The Salisbury Plain study has shown that this type of analysis can be undertaken relatively simply and provides important information about the accuracy of the features depicted in ALS models. Developments in sensor technology mean that it is reasonable to extract metric data about archaeological features from the ALS models. However without a good grasp of the accuracy of the models, through assessments such as those made in this study, the data extracted cannot be verified against 'real-world' measures and as such are only of relative use within the dataset. If comparison of feature data between datasets and geographical areas is a goal of the use of ALS data for archaeological research, then it is critical that methods for assessing geometric accuracy of ALS derivatives are developed and tested.

The LRM model of the ALS data also provided a useful way of measuring the accuracy of buffers placed around archaeological features. Although for many applications archaeological

features are best transcribed from ARS data as polylines, buffers are sometimes required for spatial analysis, such as the application of the SI. The LRM allowed an assessment of how well different buffer sizes represented the features with positive and negative topography across the landscape, thus allowing the selection of an appropriate buffer size. Preliminary analysis of this sort is hardly ever undertaken when archaeological data are spatially processed from raster pixels to linear or polygonal features, but it allows the underlying assumptions of processing techniques such as buffering to be assessed and optimised for each application.

9.3.4 Intensity

Objectives 10 and 11 of the research related to the evaluation of the ALS intensity data, both as a tool for prospection and in relation to ground based geophysical techniques. The value of the intensity data from ALS survey has been mooted (Crutchley 2010) and latterly investigated in relation to the ability to predict organic deposits from it (Challis et al. 2011a; Challis et al. 2011b). Previously, the use of intensity data was hampered by a lack of understanding of the archaeological potential of reflectance at the wavelength of the ALS sensor and also of the factors influencing the intensity measure. For example, Challis et al. (2011a) attempted to modify an intensity normalisation routine that requires the measurements of scan angle rank for each pulse by using the elevation model, as no record of scan angle rank was available. This conclusions of this approach were invalid not only because the distance from nadir to the ground surface cannot be used as a proxy for scan angle, but also because the study failed to take account of and correct for the many other factors affecting intensity values (section 3.4). In the partner publication for this piece of research, Challis et al (2009b) concluded that the lack of linear correlation between physical soil parameters and ALS intensity is due to the influence of homogeneous vegetation fraction but if the vegetation fraction was really homogeneous and contributing so significantly to the reflectance, it is difficult to see how the palaeochannel feature could have been detected in the intensity data at all. Without contemporary airborne spectral data and ground observations it is difficult to see how the impact of the soil vs. vegetation fraction could be assessed. Also as noted above (section 9.2.6), to reduce the level of uncertainty introduced by temporal variations in soil moisture, ground observations should ideally be contemporary with airborne data collection which was not possible in the latter study due to the use of archive ALS data.

The Salisbury Plain study offered the first opportunity to compare ALS intensity to calibrated narrow-band hyperspectral data of similar wavelength and contemporary geophysical and soil moisture survey. Although some progress was made with this line of investigation, detailed analysis of the intensity data was hampered by the lack of robust calibration routines available

during the study. Although archaeological features could be detected in the data captured with the Leica ALS50, the planned trial of calibration techniques developed by TU Wien was not possible during the timeframe of the study. Histogram matching to band 74 (1065nm) of the spectral data did improve the visual display for this data, statistical analysis showed a poor correlation to the spectral values recorded (section 7.7). These data also showed no correlation to the earth resistance survey and soil moisture measurements. Thus it is concluded that image matching techniques are not sufficient to improve the ALS intensity measures to the standard required to match the sensitivity of the spectral data and it remains to be seen whether techniques developed to calibrate the Riegl ALS sensor can also be applied to the Leica instrument. Critically, it is noted that even if calibration of the intensity data is possible, the analysis of spectral sensitivity for the full range of hyperspectral wavelengths (6.5.2) as part of the Salisbury Plain study suggests that at 1064nm the laser wavelength is suboptimal for archaeological prospection.

9.3.5 *The Contribution of ALS to Airborne Multi-Sensor Survey*

As anticipated, the ALS data performed well in comparison with other sensors in the Salisbury Plain study. For the Everleigh area, archive ALS data recovered 72% of all features detected in the study and 76% of features previously recorded by the HER (section 7.8). Unlike the spectral data, the ALS visualisations were shown to be unaffected by land use type, making them the key dataset for feature detection in this environment.

The principal advantage of the ALS data was the ability to profile features. This proved critical to the interpretation of archaeological features not just in the ALS data but also when overlaid with the spectral data. Although 3D and point cloud visualisations give a useful general overview of the landscape, profile mapping proved to be the most effective tool for measuring topographic detail.

In summary, in addition to being a useful prospection technique in its own right, the ALS data contributed to multi-sensor survey in two main ways. Firstly it provided a high resolution, high accuracy spatial model against which to standardise the transcriptions of the spatial data from the archive spectral and aerial photography. Secondly the ALS data provided contextual information about the upstanding features allowing improved interpretation of the digital spectral data. For these reasons it is highly advisable that ALS data are incorporated as a primary dataset in multi-sensor survey to improve quality and comparability of results.

9.3.6 *The Contribution of the Salisbury Plain Study*

The contributions of the Salisbury Plain study to advancing the use of ALS data for

archaeological prospection can be summarised as follows:

- The first quantitative assessment of the impact of a wide range of ALS visualisation techniques on archaeological feature detection, using number of features and APFL as comparative measures.
- The first study to highlight the importance of understanding what each ALS visualisation technique represents (topography or effects of topography), and how this impacts on the locational accuracy and interpretation of archaeological features.
- Development of a method for the statistical comparison of ALS-derived LRM and DEM and GCP profiles of topographic features enabling rigorous comparison of the impact of modelling techniques on interpretation of archaeological profiles.
- Assessment of the impact of the polygonisation of archaeological features identified in raster data with respect to improving the representativeness of buffer size.
- Direct statistical comparison of uncalibrated ALS intensity measures with hyperspectral data of similar wavelength showing poor correlation and therefore limiting the use of this data as a substitute for digital spectral data.
- Improved understanding of the relative value of ALS data when compared with other ARS data, specifically archive oblique aerial photography, digital spectral data and vertical 4-band NIR photography.
- Assessment of the value of ALS data as part of multi-sensor airborne survey of archaeological landscapes.

9.3.7 *Future Directions*

There is no doubt that the inception and increased use of ALS data for landscape assessment is revolutionising aerial archaeology in much the same way as aerial photography changed the discipline over the last century. Management considerations are forcing aerial archaeologists away from a dependence on aesthetically pleasing but site specific and directionally limited oblique photography of sites to more holistic methods of landscape survey. While the resolution of ALS data may not yet match that of aerial photographs, the systematic nature of the survey means that all topographic features will be recorded (within the parameters of the sensor), regardless of illumination angle and direction. Although visualisation techniques are clearly still being developed actively, the advantage of ALS survey is that the original point cloud data can be reinterpreted with each new technique, or by each new user, removing some of the subjectivity and non-replicable nature of oblique aerial photography.

Moving forward, it will be possible and necessary to extract metric information about archaeological features from the ALS data. It is possible to derive a wealth of information from the ALS data, including feature dimensions, volume and, by comparison of multiple surveys, erosion and degradation. Techniques such as the LRM which isolate microtopography from the surrounding landscape, could form the first steps in automating or semi-automating this process. Although the Salisbury Plain study has shown that deriving and recording this feature information and making use of the 2.5D nature of the rasterised data is possible with both archive data and data collected from planned acquisitions, it remains a facet of the use of ALS data that none of the published archaeological studies to date have incorporated.

In order to develop robust methods for extracting feature data, it is crucial that ALS visualisation techniques are rigorously assessed against kGPS data wherever possible to provide estimates of their accuracy. This is an aspect that has been ignored to date in the archaeological literature but underpins the use of ALS data to interpret microtopography. There have been some expressions of disappointment in the wider archaeological community when the visualisation of an ALS survey did not prove to be the panacea of feature detection that was hoped for. Understanding what each visualisation represents and with what level of error should help to mitigate these instances and providing ancillary ground observations is vital to improving the application of all modelling techniques.

Although ALS survey has been shown to be of great benefit through this study, it must be emphasised that only one aspect of the archaeological landscape – direct topographic variation - can be recorded using this sensor. It is anticipated therefore that multi-sensor survey, incorporating ALS and digital spectral or aerial photographic data will be increasingly sought after as a combined research tool. With this will come the requirement to manage the large quantities of data and to enable efficient and accurate interpretation based on feature attributes. Section 9.4 discusses some ways in which the Salisbury Plain study has contributed to multi-sensor research and digital integration of ARS data.

9.4 Developing Methods for Airborne Remote Sensing in Archaeology

9.4.1 Introduction

The integration of ARS data was perhaps the most important objective of the research, towards which the independent analysis of sensors was directed (Objective 12). The discussion here is in two themes. Firstly, the impact of employing multiple airborne sensors for archaeological prospection is discussed with reference to the Salisbury Plain study (sections 9.4.2-9.4.3). This has implications for future survey strategy; an area which there has been very little discussion,

due in part to a gap in understanding regarding the potential complementarity of airborne sensors and also to the dependence on archive data in the historic environment sector reducing the requirement for survey specification. Secondly, the efficient management of ARS data for archaeological prospection is a critical issue for heritage professionals (Cowley 2011; Powlesland 2011) and consequently methods of data comparison and reduction are in high demand, although there has been little research to date in this field (Donoghue et al. 1992; Sterazi et al. 2008; Traviglia 2008). The Salisbury Plain study investigated a number of methods for integrating ARS data in an attempt to quantify the impact of data fusion on feature detection (section 9.4.4).

9.4.2 *The Impact of Multi-Sensor Survey*

The baseline for comparison of the ARS techniques was “low level” integration, defined as the cumulative recovery of features from independent mapping from different sensors. In undertaking this comparison of feature detection rates and APFL recovery it was possible to quantify the contribution of multiple airborne sensors in this environment in comparison with the known record (section 7.7.4). As only one other study in the UK has published the comparison of detectability along these lines for an alluvial, arable-dominated landscape in the Vale of Pickering (Powlesland et al. 2006), the Salisbury Plain study represents a significant expansion of current knowledge.

The study of archive data for the Everleigh area showed the benefits of applying multiple data sets by illustrating the relative value of each of the sensors. Nine visualisation techniques were shown to be equivalent to the aerial photographic transcription of the HER in terms of feature recovery rates (table 7.6). The ALS survey was shown to be the most productive tool in this environment (section 6.6), however when the results of the spectral surveys were combined with the ALS, recovery rates were shown to rise by 10-20% (table 7.8). In this study, analysis of feature types has shown that the majority of features (76%) recorded in the HER have some topographic expression. Therefore the addition of 10-20% more features through the application of spectral data to the ALS is significant and illustrates the applicability of this survey technique to this environment.

The fact that multiple complementary sensors provided improved feature detection is not an unpredictable result given the nature of the archaeological features being surveyed, however the Salisbury Plain study provided a unique opportunity to compare to a detailed record from archive aerial transcription. In being able to compare sensors it was also possible to undertake a baseline prediction of feature certainty (table 7.10). Although uncertainty of interpretation from aerial sources always exists, there is often no logical way to quantify the level of uncertainty

regarding a particular feature. In providing a method to quantify feature certainty, this study proved the value of multiple survey techniques to this assessment (section 7.4.6). Levels of certainty can be attached to individual features to inform future ground based or aerial work allowing better strategic management of the landscape and archaeological features within it as well as targets for further research.

9.4.3 The Impact of Multiple Visualisations

The Salisbury Plain study provided the first opportunity to assess the relative gain to be made in feature detection by applying many visualisations as opposed to a single technique. Analysis showed that by combining the results of mapping from all the ALS and spectral visualisations from both acquisitions, 83% of the features previously recorded from aerial photography could be detected. By selecting only the best performing visualisations for each sensor this dropped to c.74% of the HER resource (section 7.4.4, table 7.8). This c.10% relative drop in recovery between all visualisations and the single best visualisation is also seen across all the features recorded in the study (from 90% to 82%) and highlights the importance of applying multiple visualisations.

This assessment is of course specific to the environment and data of this study, but it allows users to gauge the relative benefit of applying a large number of visualisations to ARS data compared with a single best performing visualisation in terms of features recovered versus processing and transcription time. For some applications a 10% lower feature recovery rate would be an acceptable compromise given lower processing burden, for others this would not. Analysis such as this should be undertaken in different landscape types in order to inform strategies for extracting archaeological information from ARS data.

It should also be highlighted that selection of the best performing visualisations for any dataset or environment is not possible without some form of prior assessment. In this regard a move to automated assessment of the separability of archaeological data from the background values for a variety of visualisations (in the same vein as the SI for spectral data) in a series of training areas should be encouraged as a preliminary processing step.

9.4.4 “High level” Integration of Data Sources

From the assessment of individual visualisation techniques it was possible to quantify the success of “high level” digital techniques for combining data from various sources using raster mathematics. The Salisbury Plain study provided the first quantitative comparison of such digital combination techniques against the results of feature mapping from individual techniques.

The simple overlays and the Brovey transformation for January FCC and ALS LRM data were shown to have similar rates of recovery of expected features (80% of all those detected in the single visualisations contributing to the transform), though for the May Brovey transform this increased to 88%. The Brovey technique was also shown to improve APFL compared with either of its contributing visualisations (section 7.2.3, figure 7.5) .

As with the assessment of all-versus-selected visualisation techniques presented above (section 8.4.2), these figures allow users to gauge the possible impact of digital data combinations on feature recovery and provide important new information as to the efficiency of these techniques compared with mapping from individual visualisations. The key finding of these initial steps towards digital combination was the unsuitability of the majority of ALS models as a base for digital combination of data. Even when scaled to match the value range of the spectral data, these models did not provide sufficient microtopographic detection (section 7.2.3). Only the LRM model proved suitable for combination with the spectral data in this way. Additionally it was not possible to experiment with combining data from different spectral acquisitions into the Brovey transform to assess whether global feature recovery rates could be improved. With four contributing images, the number of permutations for this transformation across a dataset as diverse as the one examined for Everleigh were too large to test visually. As mentioned above, an automated assessment of archaeological separability is a necessary development for fully exploring the permutations and therefore allowing the optimisation of this transformation.

9.4.5 *The Contribution of the Salisbury Plain Study*

The contributions of the Salisbury Plain study to advancing the use of multi-sensor methods for archaeological prospection can be summarised as follows:

- Quantitative comparison of the impact of multi-sensor survey on archaeological feature detection rates, both globally across the study and against a baseline established from transcription of archive aerial photographs.
- Derivation of a method to assess feature certainty based on multi-sensor detection rates.
- The first study to compare quantitatively feature recovery between single and multiple visualisation methods for the same data.
- The first study to compare quantitatively feature recovery between individual visualisations and their digital combinations.
- The identification of the most suitable ALS model (LRM) for digital combination with digital spectral data.

9.4.6 Future Directions

Through the course of the project it has become clear that the quantity of data collected by multiple airborne sensors is in many respects too great for traditional methods of prospection. Transcription from various visualisations is time consuming and fraught with complicated decisions regarding which methods are best for the environmental archaeological and seasonal variations that have been shown to play a great part in detectability of features. To use the ARS data that is increasingly becoming available to the heritage sector more efficiently it will be necessary to automate some stages of the feature extraction process.

While it is acknowledged that automation may not give the same results as observer-led transcription, the possibility to collect image information from multiple sources at pixel level and set in motion a decision making process that classifies the likelihood of that pixel representing an archaeological feature would be an exciting progression of the field of ARS. Developments in this field are very much in their infancy but there has been some promising progress towards semi-automated extraction of particular types of features in single datasets (Trier and Piloe 2011).

There is significant resistance to the ideas of any level of high-level automated extraction in the heritage field and concerns regarding false positives and overlooking ephemeral features are not without foundation. However these issues are not insurmountable or unquantifiable, and it is argued that based on the complementarity of different sensors as shown in this study, the incorporation of multiple datasets could significantly help to improve the quality of automated feature extraction. The keys to successful implementation of any semi-automated process would seem to be a clear understanding of the nature of the archaeological feature and how this allows its detection in ARS data. The current research has moved our understanding forwards in this regard, but there is clearly much work to be done to underpin our understanding of ARS across different environments. Without this understanding, automated extraction cannot be expected to be successful as it will not be possible to define the input parameters that represent an archaeological feature.

Currently there is also a requirement for automation of a lower order to improve our understanding of the ARS data. This study has shown that while extremely effective, visual analysis is a time consuming and subjective way to compare ARS images to a known base line. Processes such as the Separability Index are required to automate the assessment of how useful an image is for detecting archaeological features and there is a requirement for the theory of detecting contrast from the surrounding data that underpins both visual assessment and semi-automated methods such as the SI to be extended in a verifiable way to other datasets.

10 Conclusions

In conclusion it can be stated that the research has achieved the aim of assessing the full information content of airborne laser scanned and digital spectral data, providing the first systematic analysis and comparison of techniques for an area of grassland in the UK. In doing so existing methods were tested rigorously and new methods were derived and applied.

How the results of the work undertaken met each of the specific Objectives of the project was stated in section 8.10, and these results are discussed in detail along with directions for future work in Chapter 9. The research provides not only a case study for the application of ARS in a non-alluvial, non-arable landscape but, due to the systematic nature of the comparative work undertaken, can be seen to provide a series of methods applicable to ARS data analysis that are transferable to other archaeological landscapes. It is hoped that by underpinning the scientific understanding of how ARS data can be applied, the use of these data will begin to focus on specific archaeological research objectives above and beyond the prospection for new features that has dominated the field of archaeological remote sensing thus far. In doing so this research has shown that it will be possible to derive significant new information about archaeological features and their relationship to the landscape and environment around them from airborne data.

Final Thoughts

The research presented in this thesis arose from a pressing need to better understand the application of ARS techniques to archaeological research. This was prompted by the *status quo* in the discipline which was typified by opportunistic applications of a single type of airborne sensor that were often unsystematic in their approach. The most commonly applied technique, ALS, was predominantly being examined in isolation from other remote sensing techniques and although in many respects a revolutionary technology that excited broad uptake, ALS was for the most part poorly understood and applied. The same was also true for digital spectral data, but this area of research was even further disadvantaged by the considerable lack of archaeological applications of this type of sensor, particularly in the UK. This situation led to ARS data from these sensors being viewed with quiet scepticism by the archaeological community and considered to be less valuable than standard aerial photographic transcription.

The author felt that these criticisms were often underpinned by a lack of understanding of the sensor technology and how it can best be applied to archaeological research in comparison with

aerial photography. For example ALS cannot be a direct substitute for aerial photography by nature of the fact that the two techniques record different attributes of the feature; either the visible reflectance or the elevation. However combining ALS with digital spectral survey provides an opportunity to record both elevation and reflectance in a similar way to an oblique aerial photograph. This application of multi-sensor survey is clearly the direction that the discipline should move towards given the fact that what comprises an “archaeological feature” is actually a range of attributes. The fact that these sensors allow swift, systematic and accurate survey of both elevation and reflectance across large areas is an advantage that is appealing to professionals who are charged with understanding, curating and managing historic landscapes. Unfortunately the desire to apply these data has thus far outstripped the ability to do so, a fact that drove the aim of this research to assess the full information content of ALS and digital spectral data and improve our understanding of what influences the detectability of features.

On analysis of the literature it was suspected that visualisation techniques for ARS data were significantly influencing the detectability of features and the information that could be extracted about them. As there was no published quantification of the impact of many visualisation techniques on feature detectability for a non-arable site in the UK, this was the first task of the research. The assessment of archive ARS data for the Everleigh Study Area concluded that visualisation technique has a significant impact on the binary visibility of features in both the spectral and ALS data. The key findings of this part of the research are that some ALS visualisation techniques, including the most commonly applied technique of shaded relief modelling, were shown to be inappropriate for some levels of feature extraction such as accurate geolocation and profiling. In addition, the benefit of applying multiple visualisation techniques to the same data was illustrated quantitatively.

What the study of archive ARS data showed was that while for the most part the impact of ALS visualisations is predictable, providing the technique used to derive them is understood, the impact of different spectral visualisations was harder to define. Through analysis of oblique aerial photography, changes in both reflectance and topography relating to archaeological features can be detected, and herein lies a deeper issue when considering the application of other sensors to this task. Current understanding of what comprises a detectable archaeological site from the air is dominated by a century of transcription from colour or panchromatic images. During this time only a handful of studies have attempted to define the attributes of an archaeological feature that contribute to its detectability from the air and consequently identification of features is based on collective observational experience. Consequently, when analysing data from other sensors the definitions of what comprises an archaeological feature are often indistinct which makes interrogating data for appropriate attributes difficult, leading to

a reliance on visual inspection in the same vein as aerial photography.

For the Everleigh study area it was demonstrated that both archaeological features known from the NMP mapping and new potential features identified during the mapping exercise, were more detectable in the non-visible NIR wavelengths, contributing to a small but growing number of studies that have compared visible and non-visible wavelengths directly and come to the same conclusion (Hampton 1974; Traviglia 2006; Verhoeven 2011). Having demonstrated that archive spectral data could be used to detect features in temperate grass-dominated environments the obvious challenge was to improve the understanding of environmental variables that contributed to feature detectability. Review of the published literature indicated that soil moisture was likely to be a significant factor influencing spectral response of soil and also the most likely factor affecting vegetation growth and stress. Results from the present study suggest that contemporary rainfall data may be a valid indicator of archaeological potential for archive spectral data. However the Everleigh study also showed that to understand detectability better it was necessary to return to first principles and examine the environmental variables affecting feature detection. The only way to achieve this for a variable such as soil moisture that can change on a daily basis is to undertake contemporary airborne and ground survey. Consequently while archive ARS data has been demonstrated to have great potential for this environment, and should not be discounted for future study, to push the application of ARS data forward and to improve understanding of the detail of the techniques and the impact of environmental factors, it was necessary to instigate the second phase of this project, acquiring and processing ARS data and ground measurements for the Upavon study area.

The study was fortunate to secure a data acquisition from the ARSF in their 2010 season. Without this support there would have been no feasible means of collecting the simultaneous ground data collection that was shown to be critical to improving the understanding of how to apply ARS data for archaeological feature identification. It cannot be stressed how important this was to realising the more ambitious objectives of the project. The analysis of ground data allowed the development of a technique for assessing the accuracy of the representation of archaeological topography in ALS-derived models such as the LRM, the first time that this quantitative assessment has been undertaken. The study showed the importance of evaluating the ALS models thoroughly to improve our application of them, particularly in light of their potential use as base models for digital integration of data.

Work in the Upavon Study Area also illustrated how standard geophysical techniques can be applied to aid the interpretation of spectral data. Although the spatial coverage was necessarily small and not all the geophysical techniques trialled proved feasible in this environment, it is concluded that there is significant potential in further research in this field. Critical to

understanding the correlation or lack thereof between the ARS and geophysical survey measures were the direct moisture measurements taken from soil samples. It is concluded that although there are still challenges to overcome in this field, the data derived from ground survey techniques is of critical importance to improving the understanding of spectral response at the archaeological feature level, thus helping to define what an archaeological feature is in spectral terms. This knowledge is just a small part of a wider library of archaeological spectral knowledge that needs to be accrued both in the UK and elsewhere, but in undertaking this research it has been shown that there are methods that make deriving this knowledge an achievable aim for future work.

In all, the doctoral study has shown that a systematic approach to ARS data can yield significant new knowledge, providing the foundation for the continued development and evaluation of ALS and digital spectral data for archaeological research. Multi-sensor survey, although an important goal of aerial prospection in archaeology, needs to be underpinned by scientific understanding of individual sensors and accurate methods of deriving archaeological data from them. This research has shown that methods really matter in this field. By providing the first comprehensive evaluation of existing techniques and developing new methods for quantifying accuracy and integrating ground survey measurements this study has improved current understanding of a) how ALS and digital spectral imaging can be applied, b) the comparative value of these techniques, and c) the variables that affect the detection of archaeological features within them. Only by continuing work in this vein will ARS become an accurate and subtle tool for archaeological research. The goal for archaeological ARS should be the scientific and rigorous application of appropriate technologies to improving the quantity of aerial survey. The current study makes the first of many steps in realising this goal.

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Appendix 1 – LRM Script

```
#####
# # MODULE:   r.lrm
# AUTHOR(S): Rebecca Bennett, rabennett@ymail.com
# PURPOSE:   Calculates local relief model from a GRASS raster terrain map in GRASS 6.4 using the method
#            developed by Hesse 2010 "LiDAR-derived Local Relief Models - a new tool for archaeological prospection"
#            Archaeological Prospection 18.2
# COPYRIGHT: (C) 2011 by the GRASS Development Team
#
#   This program is free software under the GNU General Public
#   License (>=v2). Read the file COPYING that comes with GRASS
#   for details.
#####
#Only run if started in GRASS
if test "$GISBASE" = ""; then
  echo "You must be in GRASS GIS to run this program." >&2
  exit 1
fi
#check region and database
g.message "Check region settings and database connection (sqlite)"

g.ask type=old prompt="enter DTM" elem=cell_misc unixfile=/home/becca/LRM/settings
./home/becca/LRM/settings
if [ ! "$file" ]
then
  exit
fi
DTM=${fullname}
#make copy of DTM
g.copy rast=${DTM}.ground --o
#first stage of LRM
#lowpass filter
g.message "Stage 1 - performing low pass filter"
g.message "Enter size of low-pass filter required: "
read USERFILE
r.neighbors -c input=ground@PERMANENT output=LRM_lowpass size=$USERFILE --o
#subtract lowpass from DTM
g.message "Stage 2 - subtracting lowpass from DTM"
r.mapcalc 'LP_subtract=ground@PERMANENT-LRM_lowpass@PERMANENT'
g.message "Stage 3 - extracting zero contours"
#extract contours
r.contour input=LP_subtract@PERMANENT output=LP_contour@PERMANENT minlevel=0 maxlevel=0 step=10
#make points from lines
v.to.points input=LP_contour@PERMANENT llayer=1 type=line output=LP_contours_points dmax=10
#extract raster values for points
v.what.rast vector=LP_contours_points@PERMANENT raster=ground@PERMANENT layer=2 column=along
#interpolate from points
g.message "Stage 4 - interpolating purged DTM"
v.surf.bspline input="LP_cp_all@PERMANENT" raster="LP_purged" method="bilinear" --o
#subtract interpolated from original
g.message "Stage 5 - subtracting purged DTM from original"
r.mapcalc 'LRM_coombe_orig=ground@PERMANENT-LP_purged@PERMANENT'
#recolour to grey
r.colors map=LRM_coombe_orig@PERMANENT color=grey
gmessage "-----LRM Complete-----"
exit
```

Appendix 2 -Geophysical Survey Report

**Upavon Field Site 1: Coombe Down Enclosures, Salisbury Plain Military Training Estate
East Range, Wiltshire UK SU 176 521**

February and March 2010

Introduction

Geophysical survey was undertaken at Coombe Down Enclosures (SU176 521) in February and March 2010 in support of airborne data acquisition associated with ARSF Flight GB10-17.

Approximately 1.8ha in the vicinity of two enclosures mapped by the NMP were subject to Fluxgate gradiometer survey in January with the principle aim of providing context and accurate locational information in support of earth resistance and GPR survey of the day of the flight (4th March 2010).

The site lies on clay with shallow (<30cm topsoil) and has been heavily degraded by plough damage. At the time of the survey the site was under recently grazed, short grass. The western enclosure was clearly visible in the gradiometer survey. Although the eastern enclosure, survived as an shallow earthwork visible in the airborne laser scanned data it proved difficult to detect in the geophysical surveys.

Method

Gradiometer Survey - 25th February 2010

Gradiometer survey was undertaken using a fluxgate gradiometer (Bartington Grad 601-2) on the 25th February 2010 over 20 grids (30mx30m) laid out using a Leica System 1200 kGPS (Figure 1). Gradiometry survey is sensitive to magnetic changes caused by occupation and as such this technique was chosen to locate the bank and ditch features of the two enclosures. A plot of the gradiometer data overlain with the with the NMP transcription is given in figure 2.

Survey was undertaken in a 'zig-zag' pattern with the direction of survey aligned north-south. A traverse interval of 1m and sampling interval of 0.125m provided a sound compromise between the detail of recording and speed of survey. Data were transferred to a laptop in the field for initial quality checking and storage and were subsequently downloaded and processed in the office using Archaeosurveyor 2 (DW Consulting 2011).

Raw and corrected plots are presented in figure 3. Corrections made to the values displayed in this plots were to zero-mean each traverse to correct for instrument heading errors and 'despiking' the data using a 1SD truncation over a 2mx2m spatial filter, to remove the localised high magnitude effects from surface metal debris. To improve the visual intelligibility of the diagram the data were also clipped to 3SD ($\pm 6\text{nT}$) across the survey.

Magnetic readings were significantly weaker in the area of the eastern enclosure consequently the data were clipped further to $\pm 2\text{nT}$ in order that the bank could be mapped more easily (figure 4).

Earth Resistance Survey - 4th March 2010

Earth resistance survey was undertaken on the day of the airborne data acquisition to record the different moisture content of the eastern enclosure bank compared with its surroundings. A transect of 15m x15m was recorded using a Geoscan RM15 resistance meter with MPX multiplexer and adjustable PA20 electrode frame in twin-probe configuration. Readings were collected in traverses of 0.5m width with an interval of 0.5m, with probe spacings of 0.25m and 0.5m. The sample densities were therefore 0.25x 0.5m for the 0.25m probe separation and 0.5mx0.5m for the 0.5m probe separation. This configuration was designed to record the response from the top 0.25-0.5m of the soil column over the feature which would be most comparable to the data collected by the airborne sensor.

It was intended to survey a 30x30m area on the day of the flight to coordinate with the GPR survey, however equipment failure meant that much of the short daylight hours were lost with repeated repairs to loose electrical connections in the RM15.

The data from the 0.25m surveys for each site was merged using Geoplot 3.0 (Geoscan Research 2004). All resistance data was then imported into Archaeosurveyor 2 (DW Consulting 2011) for editing. The surveys were clipped to 3SD to remove noise caused by isolated readings with poor contact. A Gaussian high pass filter (2mx2m) was used to remove low frequency large scale spatial detail that typically represents a slowly changing geological "background" response in resistance surveys (Geoscan Research 2005). Raw and corrected plots are presented in figure 5.

Ground Penetrating Radar Survey - 4th March 2010 and 31st October 2010

GPR survey was undertaken on the same day as the airborne data collection in order to record the subsurface structure of the eastern enclosure bank. An area of 30m by 30m of data was collected with an Mala RAMAC GPR with an 800MHz antenna coinciding with the earth resistance grid (figure 1). The depth setting was medium with an estimated subsurface velocity

of ~0.1m/ns

The data were collected along parallel W-E traverses 0.5m apart in a 'zig-zag' pattern. Traces were separated by at 0.1m intervals

and recorded the amplitude of reflections through a 35ns time-window (table 1). A survey wheel was used to measure distance along the traverses.

Like the earth resistance survey, the GPR survey was configured to maximise the data collected from the top 0.5m of the soil column. It was anticipated that the GPR survey would detect the horizon between the bedrock and the bank feature (to assess its depth below the surface) and that the signal of the bank material would be different to that of the surrounding soil matrix allowing its form to be visualised through the soil column.

On the day of the survey poor battery power retention was felt to affect the results of the survey. Consequently the northern 16m area of the area was re-surveyed using the same sensor configuration on the 31st October 2010.

Data were processed using Mala GPR Easy 3D (Mala 2010). Each survey was filtered using DC adjustment, Time Gain and the mean trace was deleted.

samples	512
frequency	14692.125Hz
frequency steps	30
operator	R.Bennett, K.Ward, R.Stacey
antennas	800 MHz/Medium=10
antenna separation	0.10m
timewindow	34.84ns
stacks	3
stack exponent	4
stacking time	0.048ns
last trace	304
stop position	30.024691m
fixed increment	0.3m

Table 1: GPR Survey metadata

Results

Gradiometry

The gradiometry survey correlates well with the NMP transcription. A graphical summary of the anomalies discussed is given in figure 7 A and numbers in brackets refer to this figure.

In general there was relatively little modern disturbance with the exception of one very high anomaly at 417563 152196 and a pair of tank tracks [1]. A pair of linear anomalies [2] represent two known lynchet features that are part of the Romano-British field system surrounding the

enclosures. The western enclosure [3] is clearly visible in this survey due to its ditch deposits, however the eastern enclosure which appears to be represented only by an upstanding lynchet with no detectable ditch, is represented only by a faint linear anomaly [4].

Earth Resistance

Changes in resistance associated with the bank of the eastern enclosure that was targeted by the earth resistance transect can be seen in both the 0.25m and 0.5m earth resistance surveys although they are generally better defined in the 0.25m data. A graphical summary of the anomalies discussed is given in figure 7 B and C and numbers in brackets refer to this figure.

Both surveys detected a roughly 'L-shaped' high resistance anomaly to the west of the enclosure bank [1]. It is postulated that this is a modern feature relating to compression of the earth associated with tank manoeuvres in the vicinity. The surveys also showed small amorphous areas of lower resistance [3]. The enclosure bank was typified by an area of slightly increased resistance running SE-NW across the survey [2]. Although the changes in resistance indicate the presence of the remains of the bank in this area, the range of values recorded in this transect is not large.

Ground Penetrating Radar

Figures 8a and 8B show the 1-10ns timeslices (each 1 reading thick) of the March GPR survey. From the other survey techniques employed it was expected that the bank feature would bisect the grid in a SE-NW direction but no evidence of the bank can be seen.

Figures 9a and 9B show the timeslices of the 15m transect that was resurveyed in October. It can be seen that the bank was also not detected in the repeat survey.

Conclusion

The gradiometer survey successfully located and identified features mapped by the NMP in the Coombe Down Area. Further investigation of the bank of the eastern enclosure revealed that this was detectable in both the earth resistance and gradiometer data though not in the GPR survey. From concurrent soil auger survey it is known that that the maximum depth to bedrock in the area of the GPR survey is 30cm therefore the choice of antennae is appropriate for the feature selected and the repetition of the survey results in October with a new battery pack rules out equipment failure. This lends to the conclusion that that the difference in matrix between the bank and the surrounding material was not significant enough to be detectable with this technique.

The amorphous nature of the eastern bank feature in both the gradiometry and earth resistance

surveys stands in contrast with the eastern enclosure, emphasising the heavy plough damage and spreading this upstanding feature has sustained. It is likely that the upstanding features of the eastern most enclosure were a) originally less substantial structures than those to the west and b) have been more severely degraded than the features comprising the western enclosure and surrounding field system due to the macrotopography of the field. The remains of the eastern enclosure are therefore less easy to detect using survey techniques employed.

Survey Notes

Surveyed by Kate Armstrong, Rebecca Bennett, Rachel Stacey, Kate Ward, Matthew Webster, Sarah Yarnall

Weather:

25th February cloudy dry cold

4th March 2010, clear, dry light breeze

31st October 2010, clear, cold, dry

References

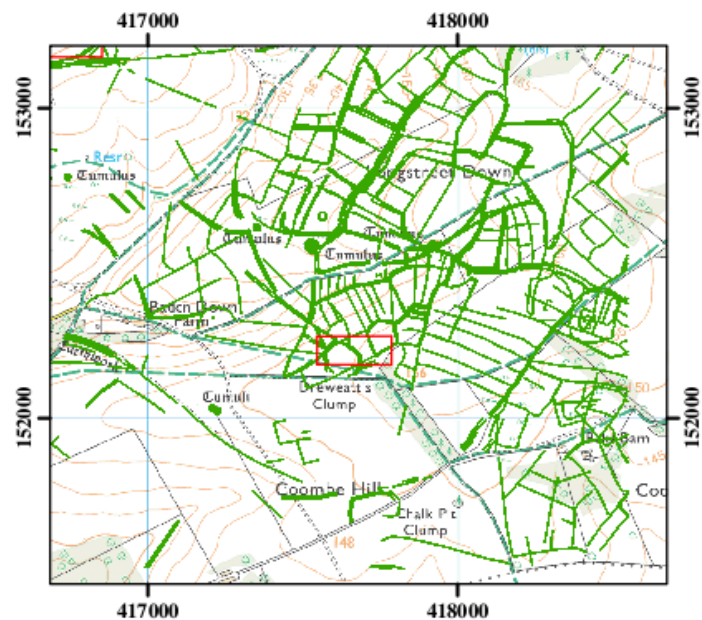
DW Consulting. 2011. *Archaeosurveyor*. DW Consulting.

English Heritage. 2008. *Geophysical Survey in Archaeological Field Evaluation* 2nd ed. Swindon: English Heritage.

Geoscan Research. 2004. *Geoplot*. Geoscan Research.

Gaffney, C., and Gater, J. 2004. *Revealing the Buried Past: Geophysics for archaeologists*. Stroud: Tempus.

Mala GeoScience. 2000. *Easy 3D*. Mala.



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An Ordnance Survey Edina supplied service

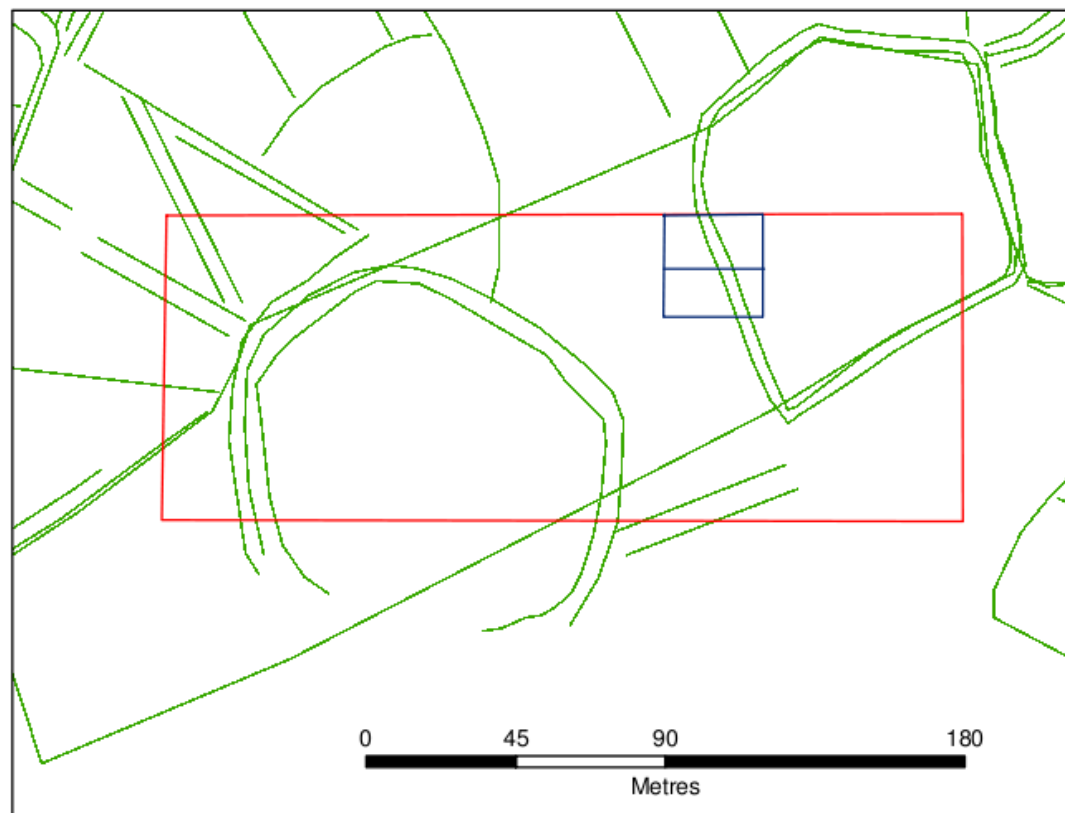
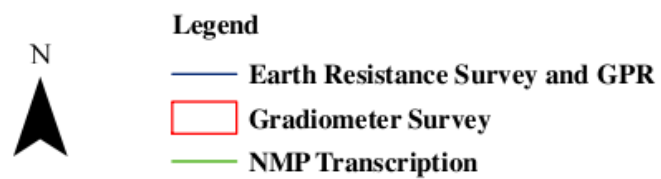


Figure 1: Area of Geophysical Survey, Coombe Down Enclosures, SPTA, Wiltshire SU 176 521

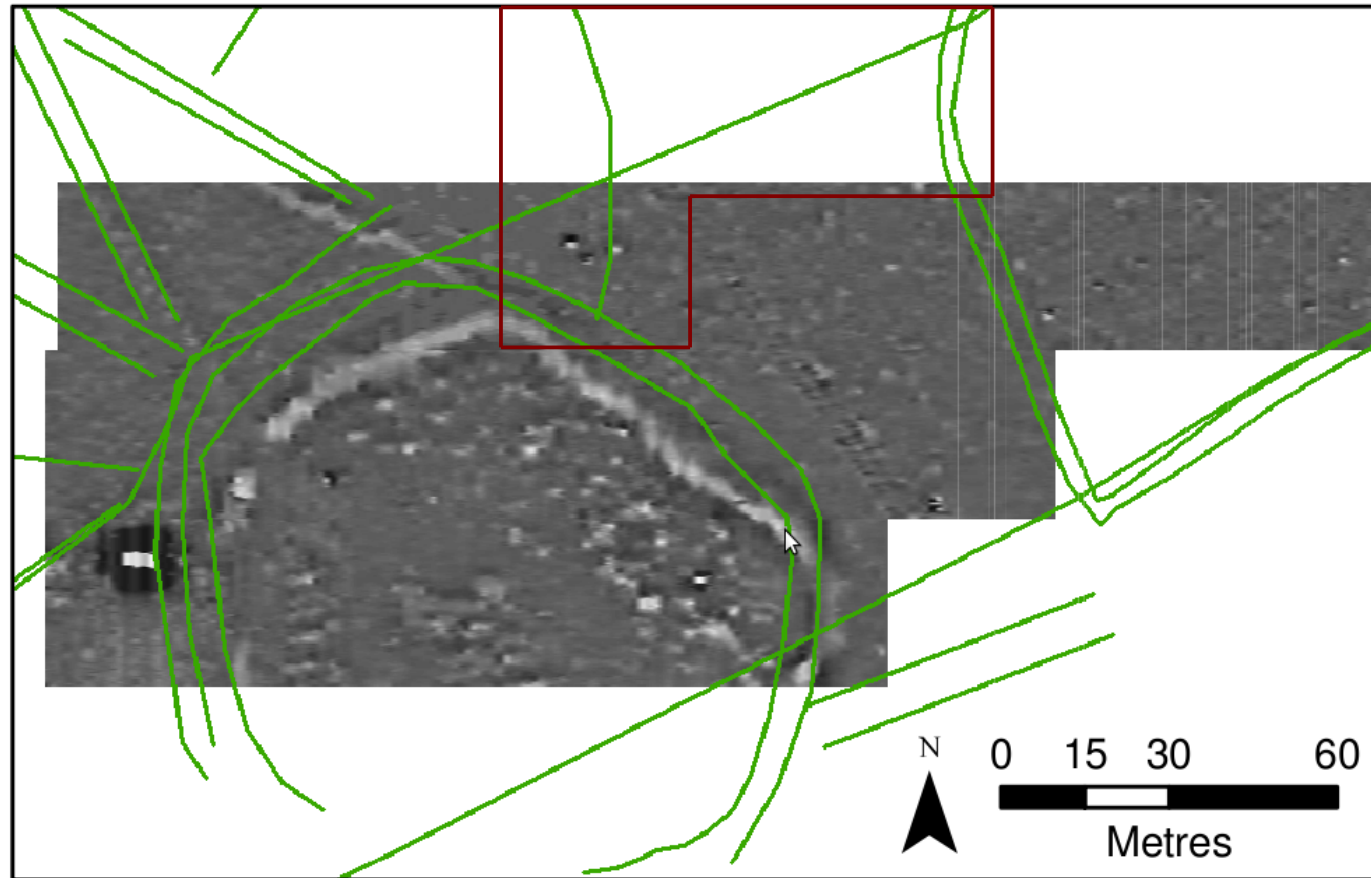
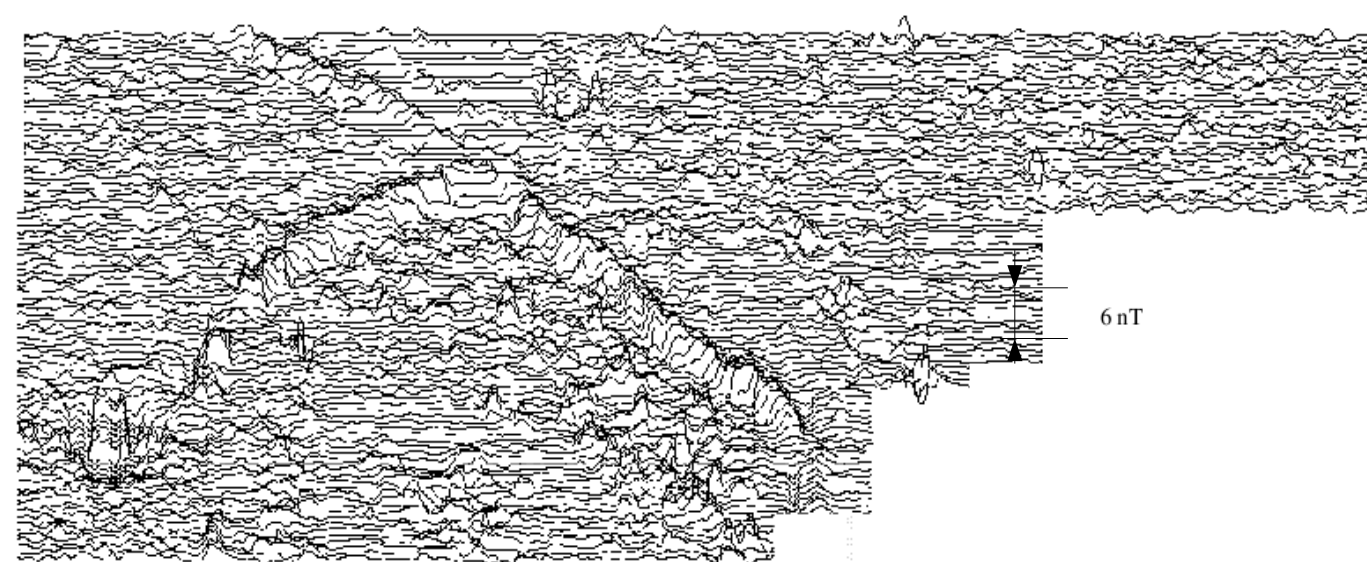


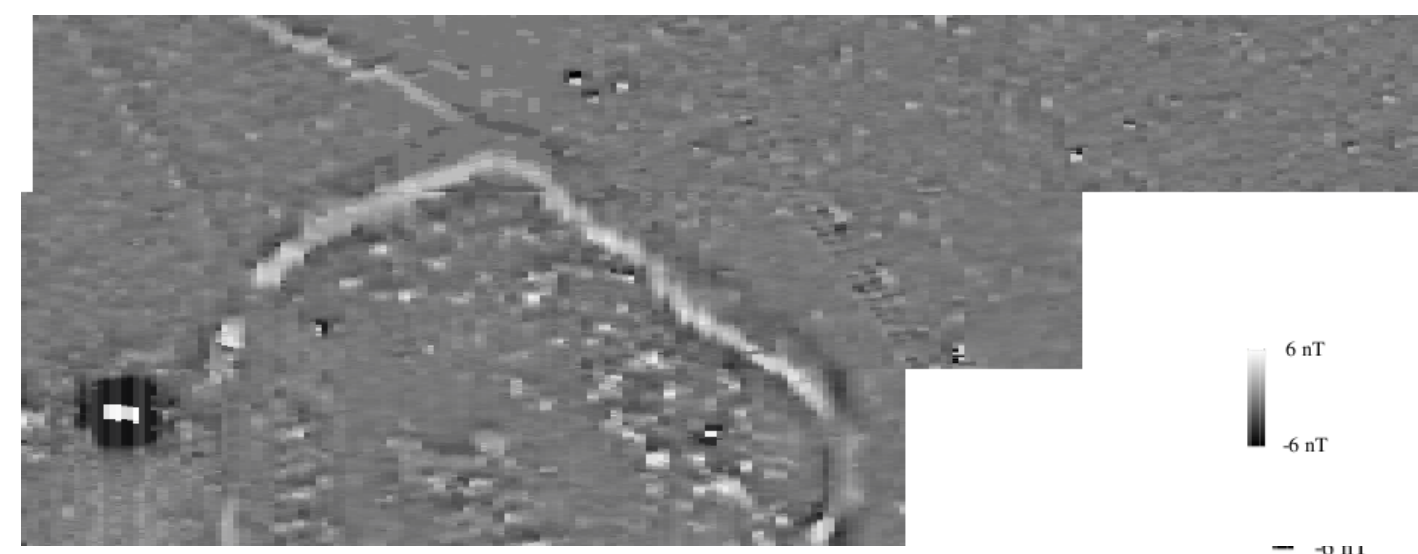
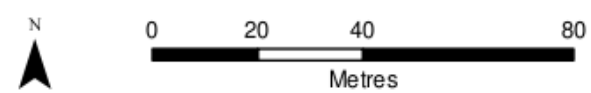
Figure 2: Gradiometry survey (shown as a linear greyscale image from $\pm 6nT$ overlain with NMP Transcription (Red denotes area of eastern enclosure, figure 4)



A) linear greyscale plot of raw gradiometry data

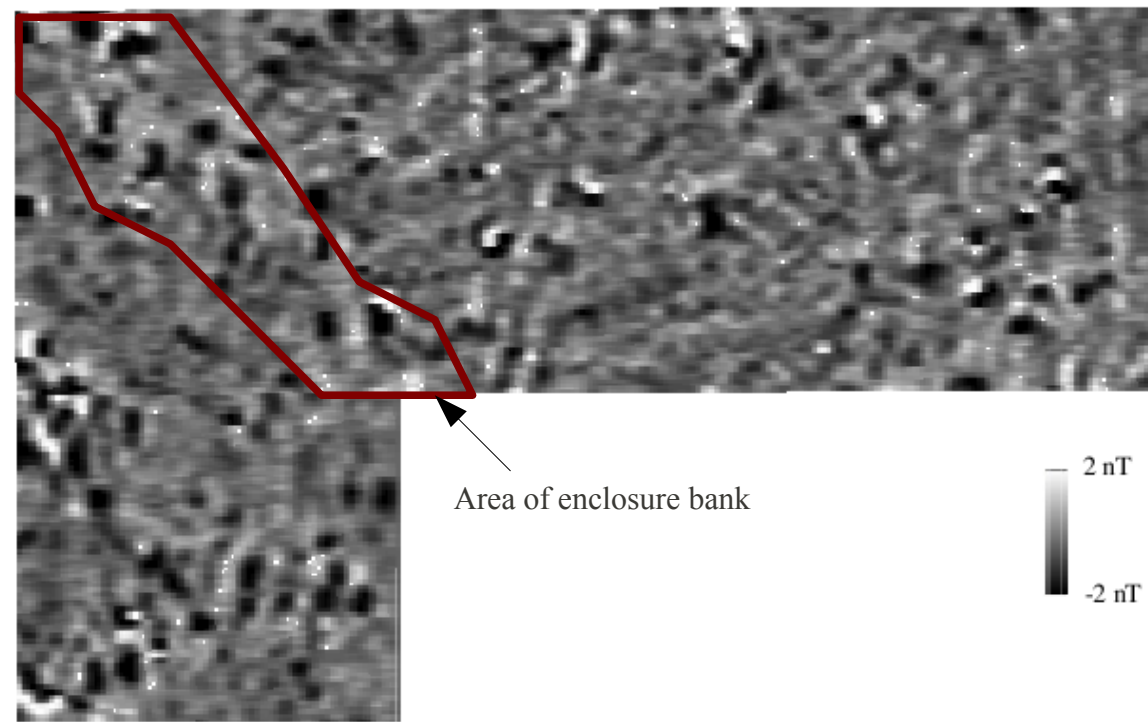


B) Traceplot of clipped data

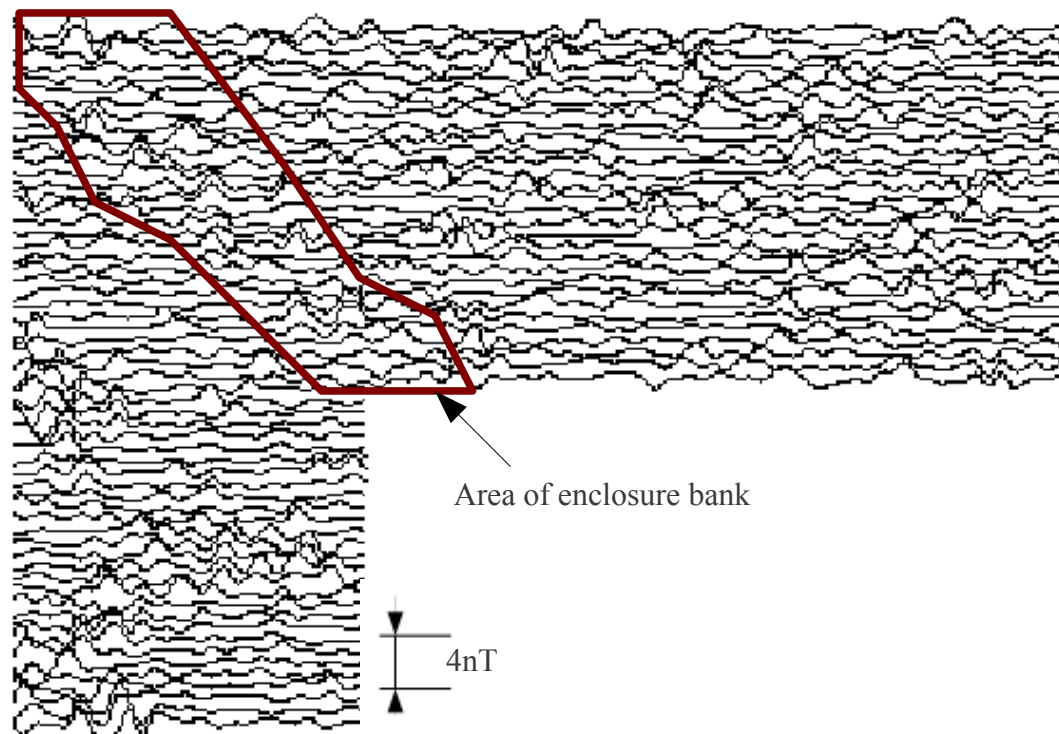


C) c) Processed Gradiometer Data

Figure 3: Gradiometry Survey Plots



A) linear greyscale plot of processed gradiometer surey of eastern enclosure bank



B) Traceplot of clipped data

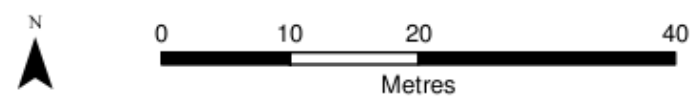
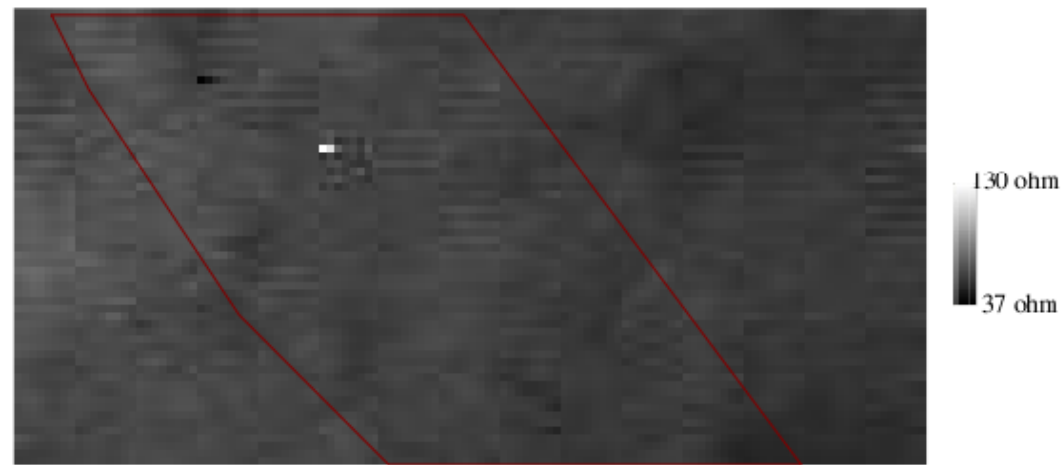
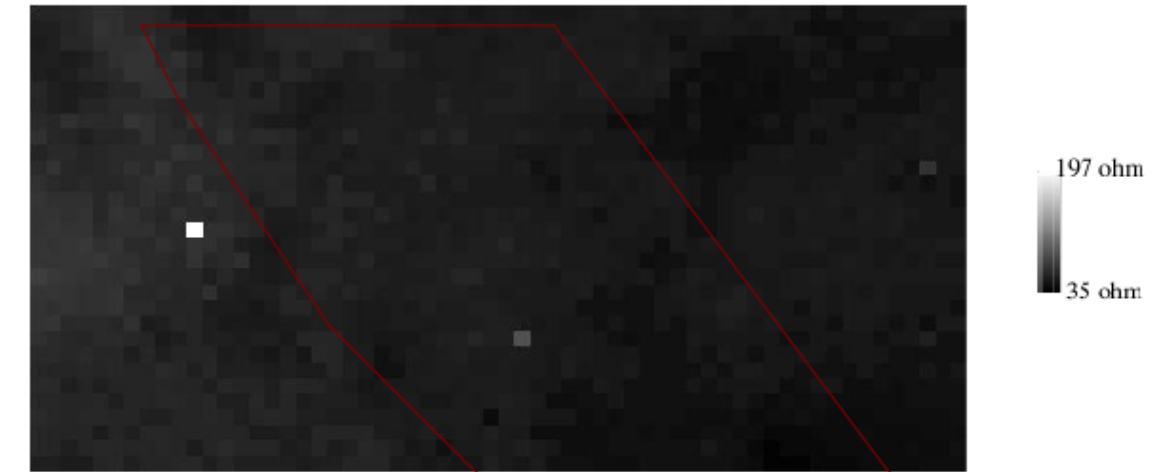


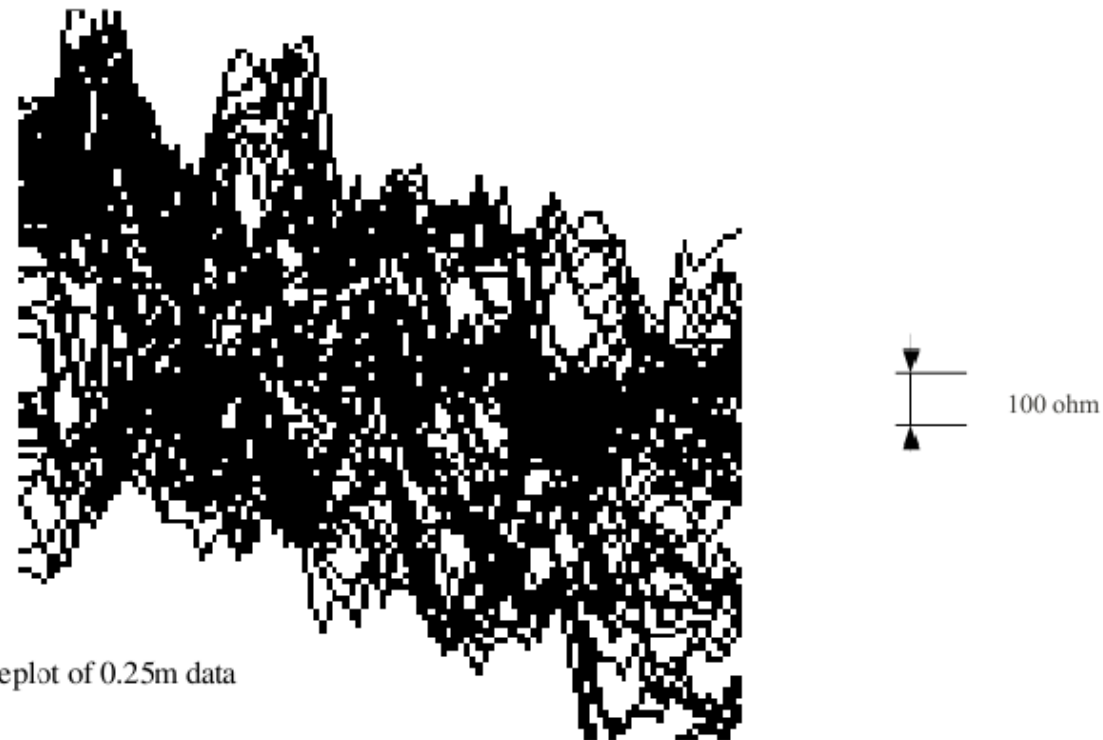
Figure 4: Eastern Enclosure Gradiometry Survey Plots



A) linear greyscale plot of raw 0.25m earth resistance data



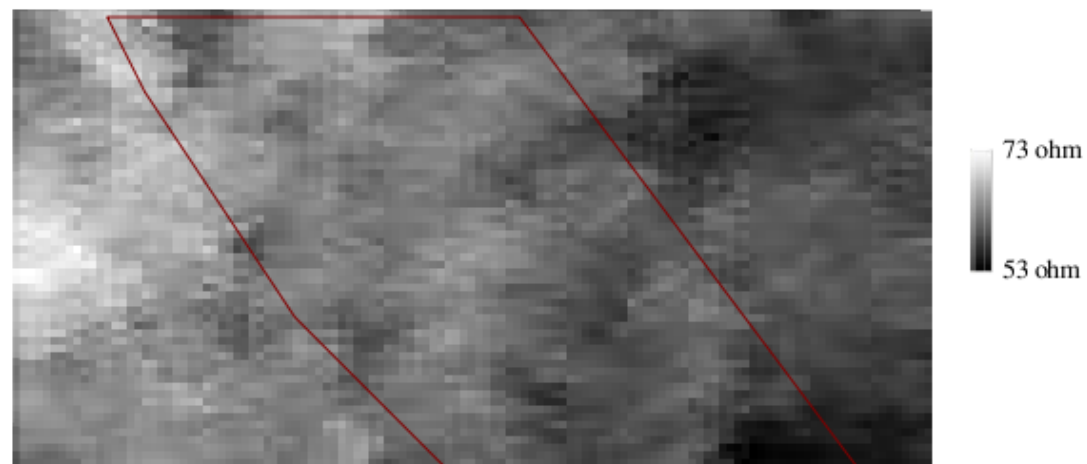
A) linear greyscale plot of raw 0.5m earth resistance data



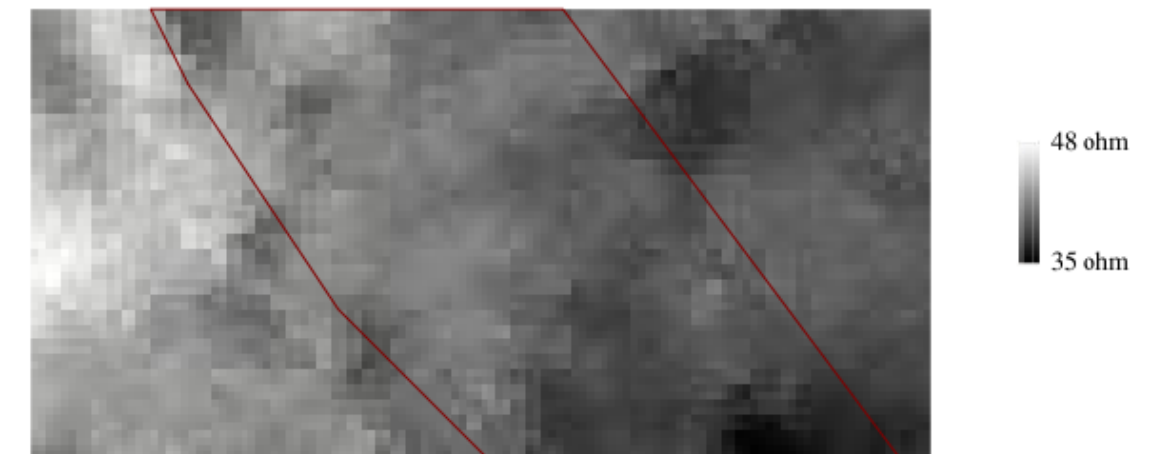
B) Traceplot of 0.25m data



B) Traceplot of 0.5m data



C) Processed 0.25m earth resistance data



C) Processed 0.5m earth resistance data

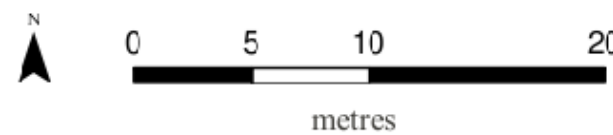
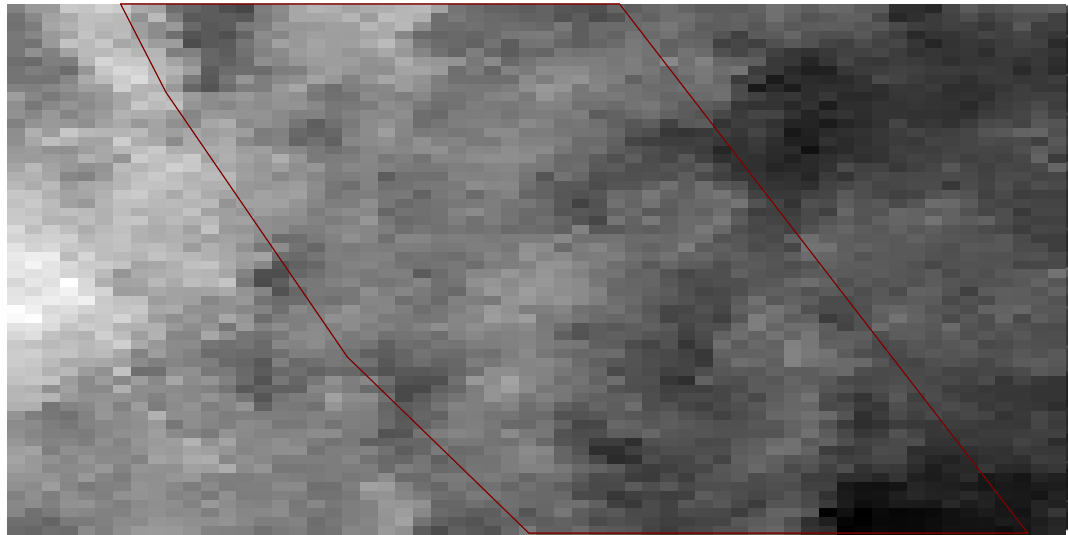
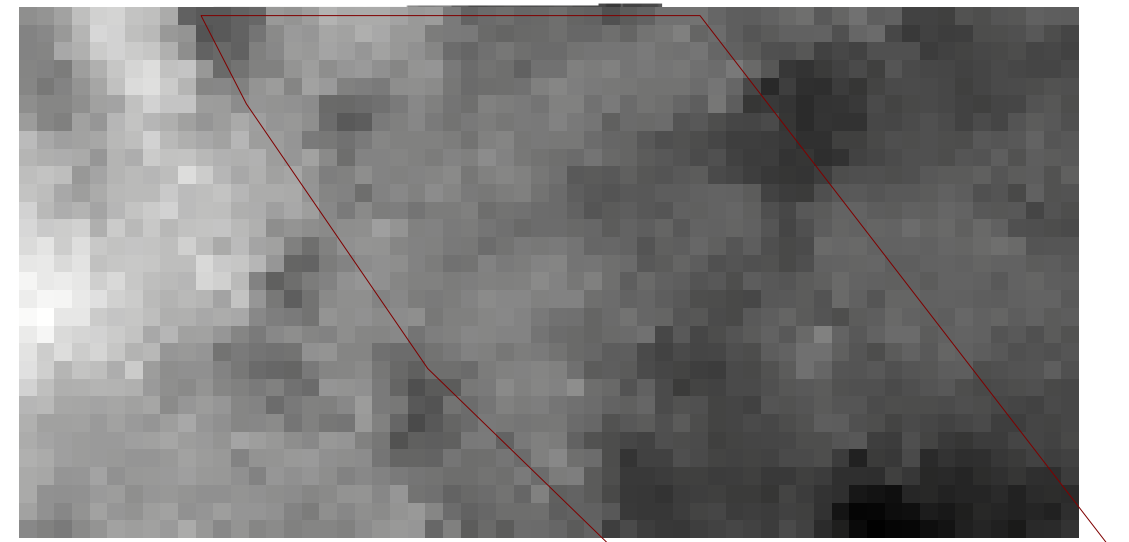


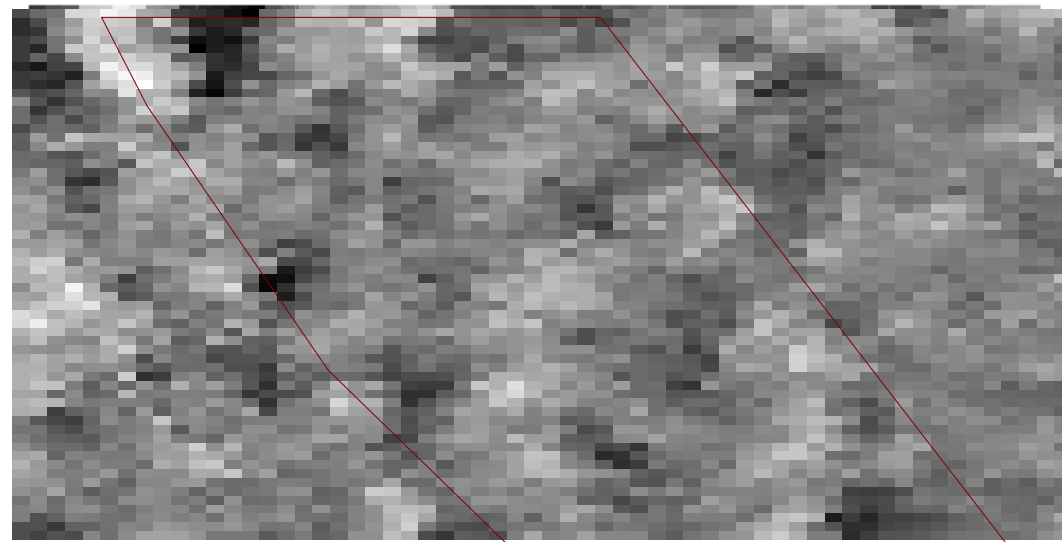
Figure 5: Earth Resistance Data (Approximate area of bank outlined in red)



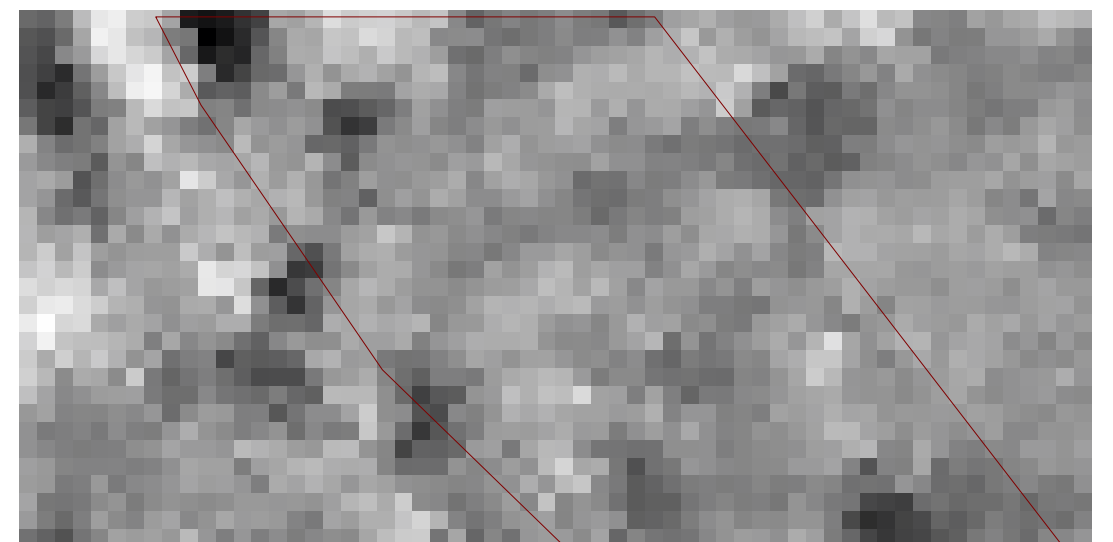
A) 0.25m Earth Resistance Data



C) Processed 0.5m Earth Resistance Data



B) High Pass filter (2mx2m) of 0.25m earth resistance data



D) High Pass Filter of 0.5m earth resistance data

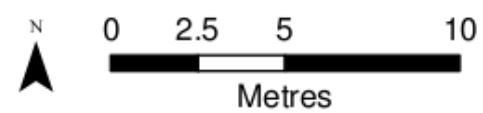
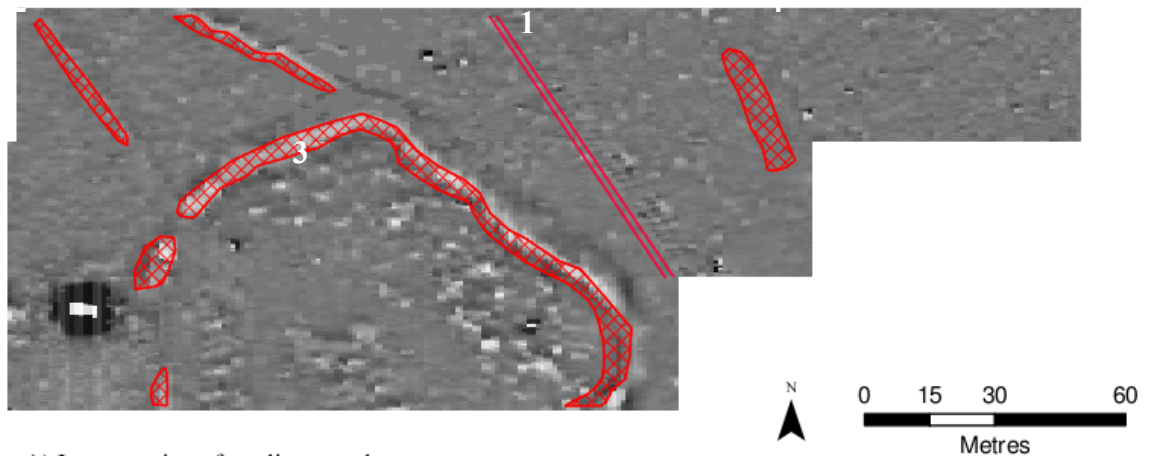
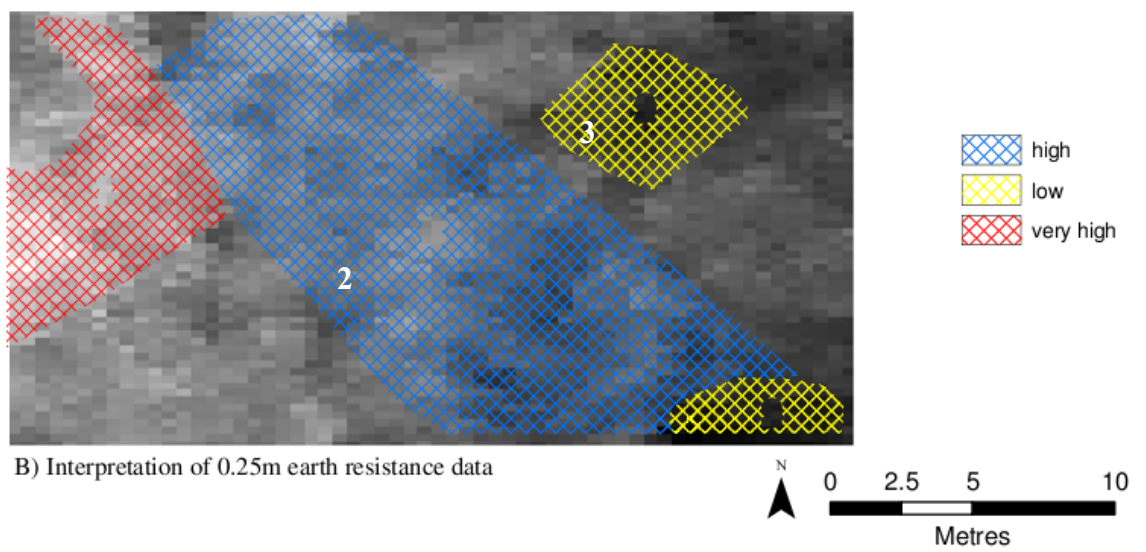


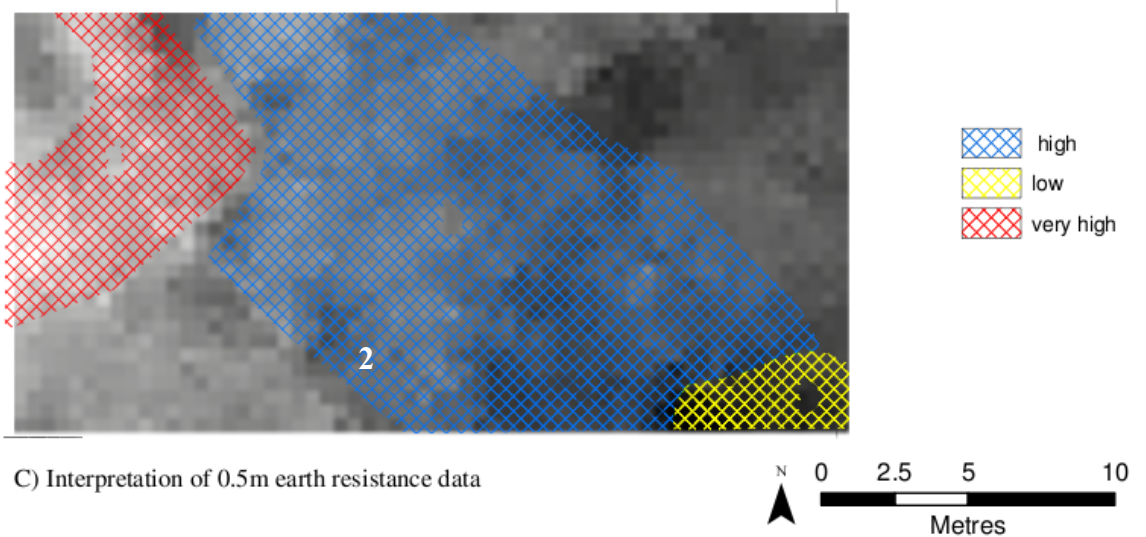
Figure 6: High Pass Filtered Earth Resistance Data (Area of bank outlined in red)



A) Interpretation of gradiometer data



B) Interpretation of 0.25m earth resistance data



C) Interpretation of 0.5m earth resistance data

Figure 7: Interpretation of geophysical surveys

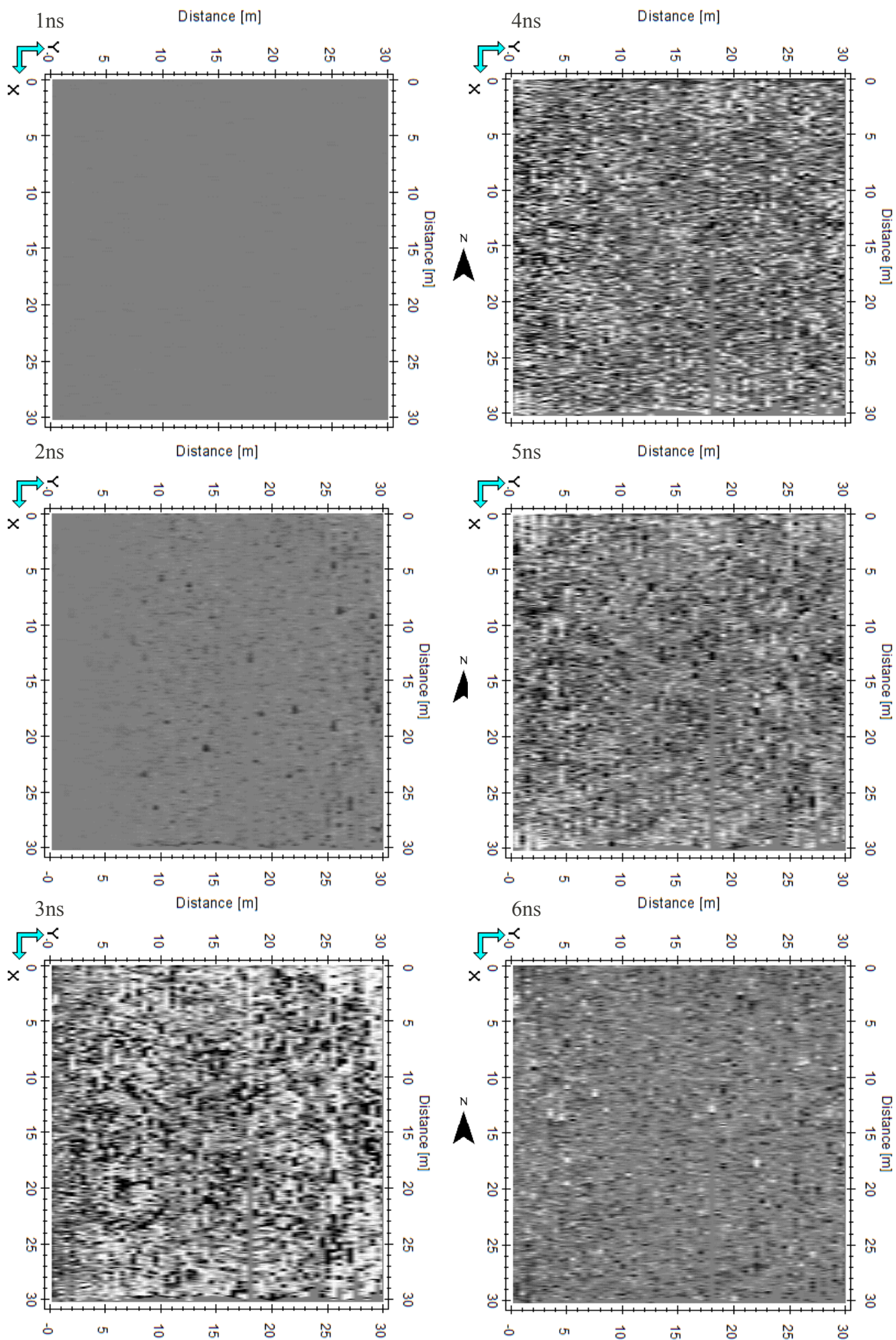
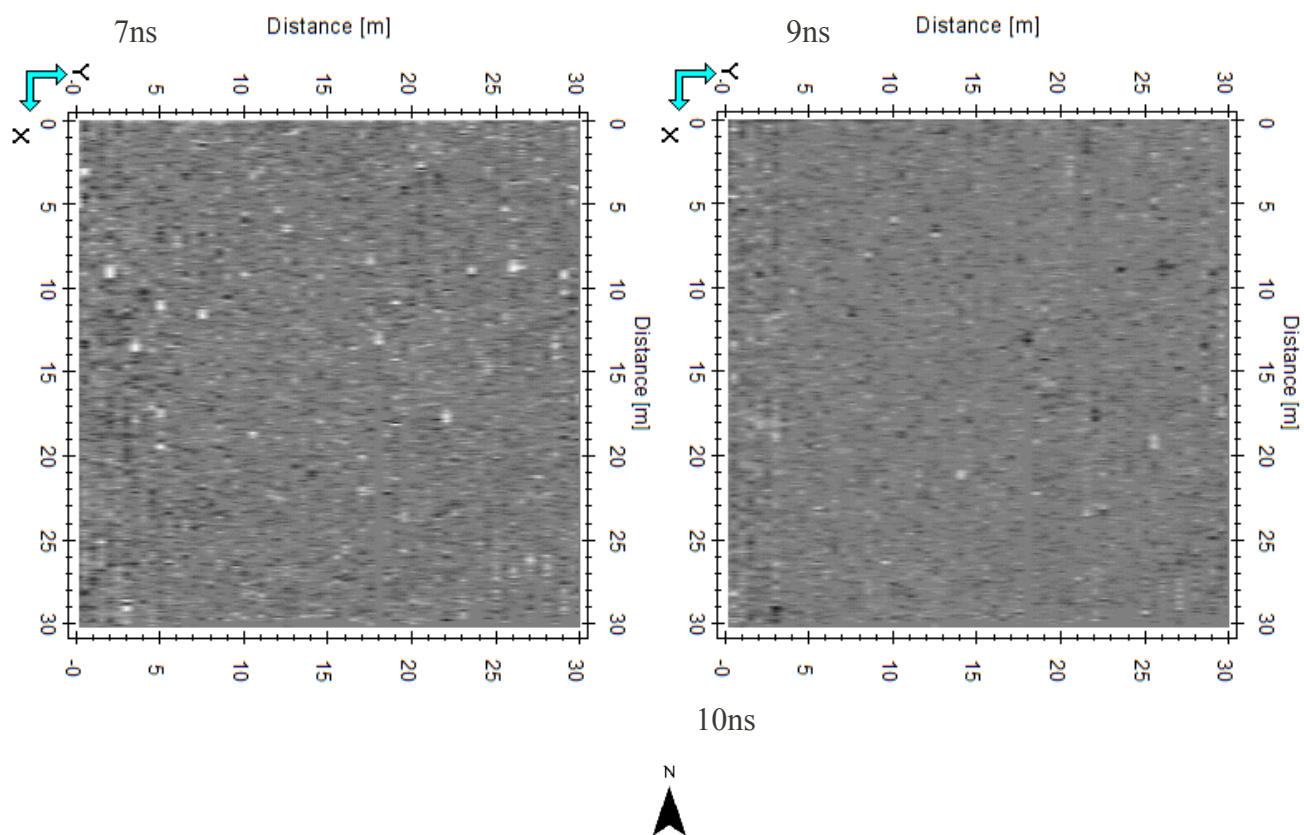


Figure 8a: March Survey800MHz Timeslices 1-6ns



View 0-10ns at 15m south of origin

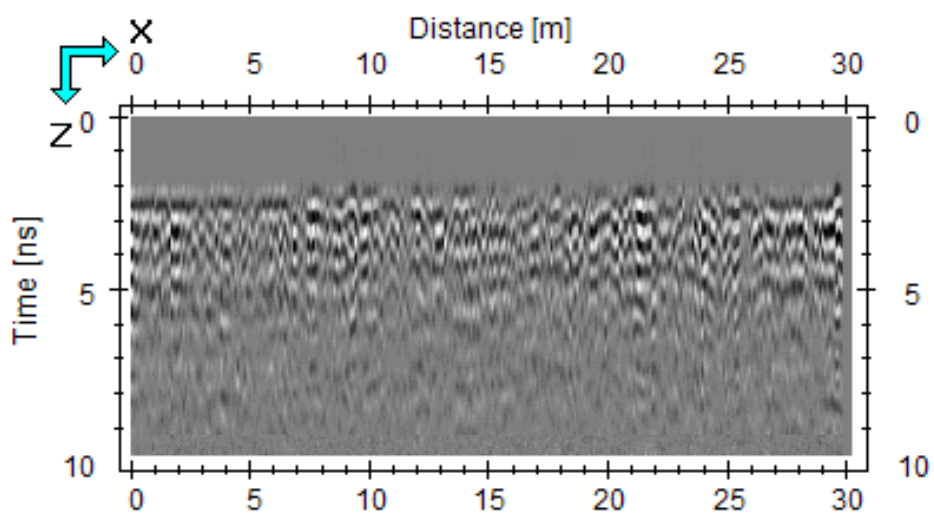


Figure 8b: March Survey800MHz Timeslices 7-8ns

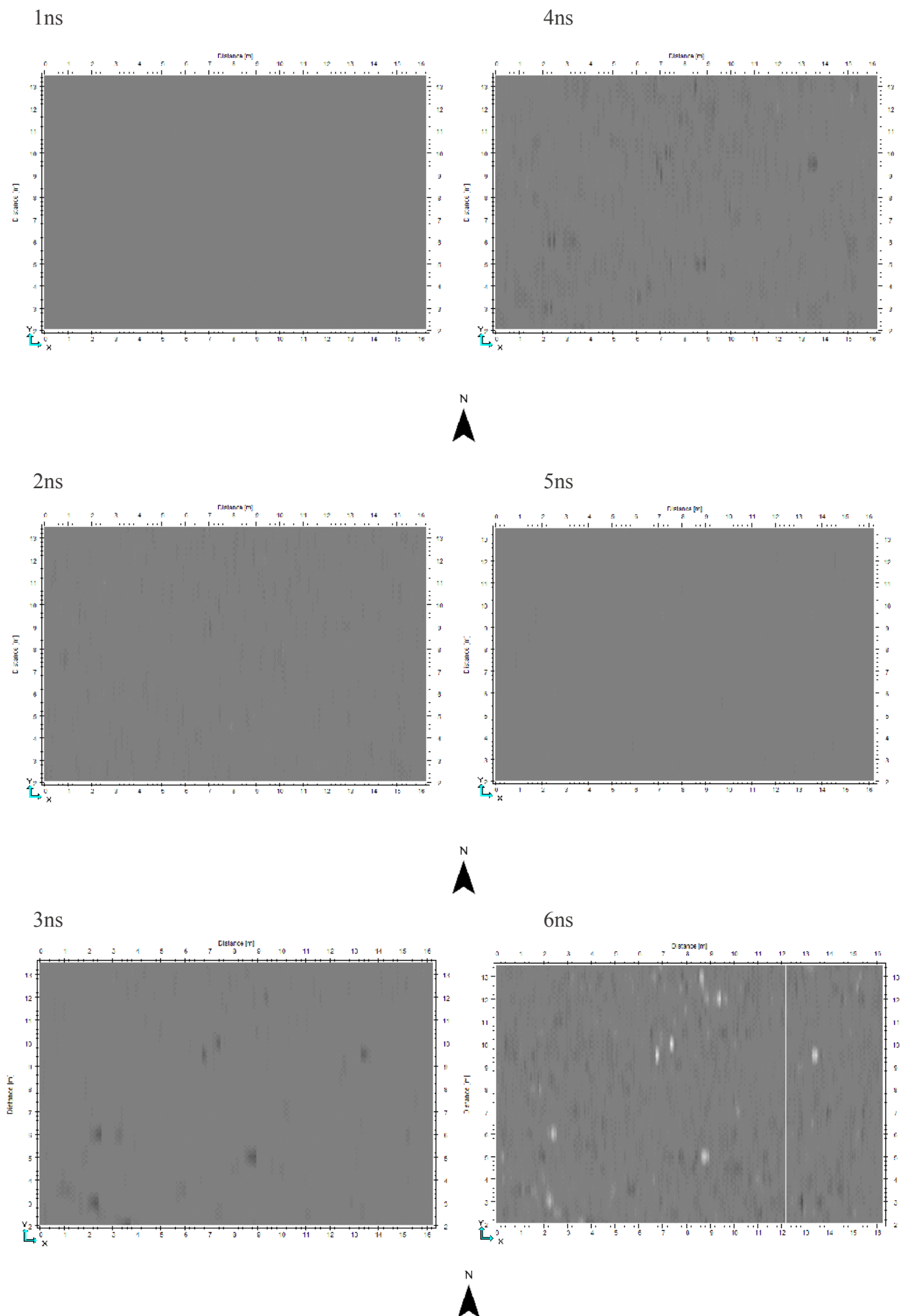


Figure 9a: October Survey 800MHz Timeslices 1-6ns

View 0-10ns at 7.5m south of origin

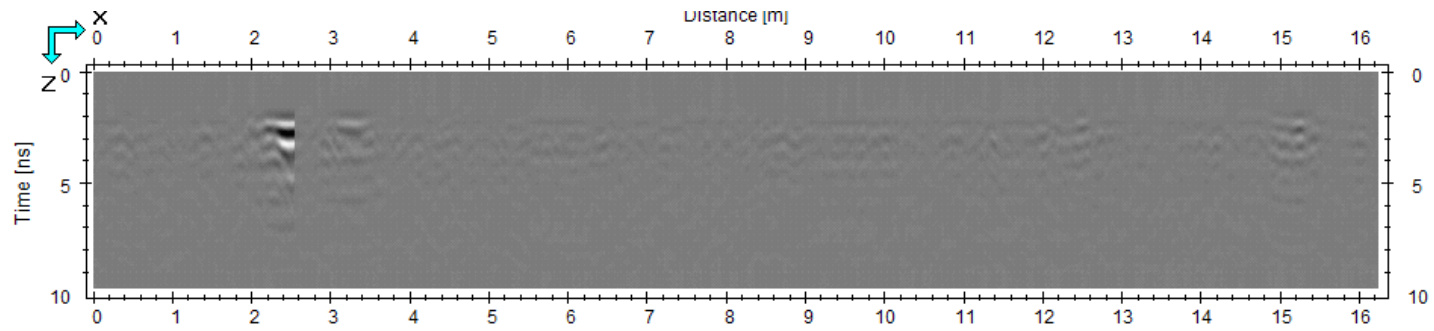


Figure 9b: October Survey 800MHz view